Factors Affecting Color Appearance and Measurement by Psychophysical Methods.

Christian James Bartleson

Submitted in partial fulfillment of
the requirements for the degree of
Doctor of Philosophy

The City University
Department of Ophthalmic Optics
and Visual Science

January 1977

Table of Contents

(Table of Contents - continued)

Tables

Illustrations

(Illustrations - continued)

Acknowledgements

This work has been supported in part by a research grant from the Trustees of the Illuminating Engineering Research Institute (USA) under IERI Project 110, made possible by the cooperation of the Board of Trustees of the Munsell Color Foundation. I wish to express my appreciation for that support and also to thank Mr. C.L. Crouch Director of Research of the Illuminating Engineering Research Institute, and Miss D. Nickerson and Mr. N. Macbeth, who served as Presidents of the Munsell Color Foundation during this period, for their encouragement and assistance.

In addition, I wish to acknowledge and thank Kodak Limited for a grant in aid which provided partial support for the initial work on this research.

I am greatly indebted to Professor R.W.G. Hunt and Dr. C.A. Padgham of the Department of Ophthalmic Optics and Visual Science of The City University for their help and encouragement throughout all of this research. Their suggestions and discussions have been most helpful.

I am also grateful for the opportunity to have had a considerable number of discussions of this work with people who kindly sacrificed their time to exchange ideas and information. My thanks go to Dr. M.R. Pointer of Kodak Limited, Dr. Y. Nayatani of the Electrotechnical Laboratory of Japan, Dr. W.S. Stiles, Dr. K. Richter of the Bundesanstalt für Materialprüfung, Professor T. Indow of Keio University, and especially to Dr. G. Wyszecki of the National Research Council of Canada who spent many hours on numerous occasions discussing each phase of the research throughout its entire course.

I offer my sincere thanks to the anonymous observers who carried out the laborious work of the experiments and without whose help it would not have been possible to conduct the research. Finally, my deepest gratitude goes to my wife, Trudy, who helped in many ways, suffered my concentration, and provided encouragement for the entire undertaking.

Abstract

Chromatic adaptation has been studied by applying methods of direct scaling to color appearances of stimuli perceived under different conditions of adaptation. This study differs from previous work in a number of ways. The color appearances of surface color stimuli were scaled by both magnitude estimation and magnitude production psychophysical methods. Changes in color appearances resulting from variations in correlated color temperature of adapting illumination, luminance factors of samples, illuminance, and surround induction conditions were scaled by a group of seven observers who had been trained to describe their perceptions in a uniform manner. This factorial approach to chromatic adaptation-influences on color appearance has yielded information about changes throughout a color solid rather than a single planar section of that solid. A distinction was made between absolute and relative attributes of color appearance.

Evaluations of both internal and external consistency indicate that the data generated have relatively high precision and validity.

The results indicate that chromatic adaptation induces smooth, continuous changes in color appearance. The nature of these changes depends upon correlated color temperature, luminance factor, and illuminance of surface color stimuli. Saturation, or colorfulness, is most susceptible to change and is highly dependent upon luminance factor and illuminance in addition to color temperature. These dependencies are systematic and explicit in the results presented here. Hue appearance of a given sample depends primarily upon color temperature of adapting illumination. Little or no change in hue was found for the range of variation in illuminance and luminance factor included in this study. In general, the hues of all stimuli change with adaptation but there are important exceptions.

The results do not support a linear model for the chromatic adaptation process.

I. Introduction

The term 'chromatic adaptation' derives from Greek and Latin words: Latin 'adaptare' meaning to adjust and Greek 'κρουμα' referring to color. In the general sense we use the word adaptation to describe a process of favorable or useful adjustment by an organism to environmental conditions. Cannon (1939)[65] called such compensatory processes, by which any organism achieves a steady physiological state to counteract or normalize changes in external or internal conditions, a process of 'homeostasis'. This implies a tendency toward constancy; undoubtedly an important factor in the survival of an organism amidst the welter of variable conditions imposed upon it. In a much more restricted sense, physiologists have used the word adaptation to describe sensory processes involving the action of specific receptor systems to variations in external stimulation. Aubert (1865)[6] was among the first to study such changes in visual sensitivity with variation in light intensity and he applied the name 'adaptation' to that adjustment. Interest in adaptation, thus construed, arose from earlier fascination with after-images. Boring (1942)[32] points out that phenomenological reports of these effects can be traced back to Aristotle and Ptolemy and are described in the works of Alhazen and Leonardo da Vinci. Newton showed interest as well, for it is reported (Brewster 1831)[51] that in 1691, in response to a query by John Locke about Robert Boyle's account of after-images (v. Plateau 1878)[268], Newton gazed at a mirrored image of the sun and subsequently closeted himself in a dark room for three days to try to rid himself of the after-image.

Much of this early interest was either frivolous or unsystematic attempts to satisfy idle curiosity. However, during the eighteenth century the concept of after-images as a manifestation of visual 'fatigue' - a concept later developed by Helmholtz (1866)[126] - was put forward in Germany (Scherffer 1765, 1785)[297,298] and England (Darwin 1786)[71]. It was this idea of adaptation as a fatiguing of the visual sensitivities that was the basis for Aubert's studies of light and dark adaptation. Shortly thereafter, working in Helmholtz's laboratory at the University of Heidelberg, Exner (1868)[97] undertook what is probably the first systematic study of chromatic adaptation; although his primary interest was in providing support for the Young-Helmholtz theory of color vision. Similar work continued in other places during the close of the nineteenth century (e.g., Aitken 1873; Burch 1898)[1,58].

We know from the large body of work that has followed these early efforts that the fatigue concept is too narrow a view to account for the complex changes in vision that may be induced by variations in external stimulation. Sensory visual systems operate to provide the organism with basically two different kinds of information: response to rapid changes and to temporally extended changes. Adaptation acts "so as to transmit any rapid changes in the environment, but ... hides any long-maintained conditions" (Hecht 1934)[122].

When modified by the term 'chromatic' this concept is usually taken to mean the alterations to sensitivity arising as a consequence of exposure to light of different spectral selectivity from that which obtains with the unstimulated or neutral state of the organism. That exposure may be direct, from a self-luminous stimulus, or indirect from a non-self-luminous stimulus object. In the latter case, the phrase 'chromatic induction' is often used; particularly if interest centers about changes in color appearances of stimuli presented in spatial relation to other stimuli in the field of view. The consequent changes in adaptation states of the organism are generally both rapid and temporally extended (Katz 1930; Schouten and Ornstein 1939; Dowling 1967)[202,302,82].

Studies of chromatic adaptation usually have been conducted with one of two different objectives in mind. Some studies have been carried out in attempts to analyze the physiological properties of the visual mechanism. That objective is basically theoretical in purpose. It seeks to increase our understanding of the mechanism of vision. Other studies have attempted to elucidate psychophysical relations among attributes of color appearance according to exposure to illumination of different spectral selectivities. This objective may be described as practical in the sense that it strives for establishment of useful engineering data. Assessment of color rendering properties of illumination systems, realistic transformations of color appearances with changes in quality of illumination, and analysis of color image reproduction are among those problems that require a quantitative knowledge of the manner in which color appearance varies with chromatic adaptation. The need for such data has been emphasized many times (e.g., Nickerson 1963)[256].

The objective of the research to be reported here is applied in the sense just described. In particular, the primary objective of this research is to provide basic data which may be used to derive a method of predicting color appearances of surface color stimuli over a limited range of adaptation conditions of general interest in commerce and industry. A subsidiary objective is to study and develop the application of direct scaling techniques to the measurement of color appearance in a manner such that the experimental data will have broad application. To accomplish this, attributes of color appearance have been scaled under a number of stimulus conditions. The influence on perceived color of color temperature of adaptation, illuminance, luminance factor, and the effect of an inducing surround have been studied. The resultant data describe systematic variations in several attributes of color throughout a complete color solid. In the past, experiments on chromatic adaptation typically have concerned only planar sections of the total color solid. It is anticipated that this research will provide data which describe adaptation-induced variations in color appearance in a more complete manner. Accordingly, these data should afford an opportunity to evaluate transformation models of chromatic adaptation with a thoroughness that has not been possible before. In addition, the results presented here should offer a basis for developing new multi-dimensional transformation expressions.

The remainder of this section will discuss various considerations that provide the bases for the experimental method and design used in this research. A brief, general review will first be made of the physiological evidence bearing on chromatic adaptation in order merely to provide the pertinent background information with which to assess what follows. What has been called chromatic adaptation theory will be addressed next. That will in turn be followed by a discussion of methods for experimental investigation of chromatic adaptation used by other workers. A brief examination of direct scaling methodology will be presented and, finally, a clarification of the color appearance dimensions, attributes, and modes of appearance - with particular emphasis on the surface color mode of appearance - studied in this research will be made.

Physiological bases for chromatic adaptation.

The initial step in the chain of reactions that comprise an adaptive adjustment involves the photolabile pigments of the visual receptors (e.g., Dartnall 1972)[70]. Presumably, there are three such pigments associated with the cones and a fourth for the rods. The action spectra of the cone photopigments are not in each case simply linear transforms of the CIE (Commission Internationale de l'Éclairage) standard observer's color mixture functions (e.g., Brindley 1970)[55]. Large changes in sensitivity may be brought about with very little bleaching or structural rearrangement of the photopigments (v., Granit and Therman 1938; Granit and Svaetichin 1938; Granit 1962; Rushton 1958, 1965c)[115,114,113,280,286]. In addition, rapid changes in adaptation occur in time periods too brief to involve bleaching or regeneration of photopigments (v. Crawford 1947; Baker 1953; Bouman 1952, 1955; Boynton, Bush and Enoch 1954; Boynton 1958; Battersby and Wagman 1959)[69,8,35,36,40,24]. Although the visual pigments may play an important role in the initiation of adaptation, they apparently cannot be completely responsible for adaptational variations in sensitivity. Changes in ionic permeability and conductance in the outer segments of the receptors, as a reaction to absorption of photons, ultimately give rise to neuroelectrical signals that are passed along through axons and synapses to higher neural levels. At these higher levels within the retina, electrical pulse-trains are found which vary in polarization with wavelength of light stimulation (e.g., Granit and Svaetichin 1938; MacNichol and Svaetichin 1958)[114,239]. One type of signal varies only in strength as wavelength is changed. Two other types show changes in strength and polarity with wavelength but their spectral shapes and the wavelengths at which reversals of polarity occur are different. The specific characteristics of these coded chromatic response signals vary with adaptation to illumination of different spectral selectivity. A large part of the adaptational sensitivity adjustment may take place within the retina, then. However, not all adaptational adjustment can be attributed to rearrangement of retinal response characteristics. Electrical activity of the lateral geniculate nucleus of the thalamus is found to be very similar to that of the retinal ganglion cells (Hubel and Wiesel 1961; Wiesel and Hubel 1966; DeValois 1965)[149,356,73] and opponent chromatic response organization is also found in the striate cortex of the occipital lobes of the brain (Hubel and Wiesel 1959, 1962, 1968)[148,150,151]. Electrophysiological measurements at the geniculate nucleus and electroencephalographic measurements at the occipital cortex (Zubek and Welch 1963)[375] show adaptational effects. It has been demonstrated that spectral sensitivities at these higher levels, both within the retina and more proximal stages, are not simply related to receptor sensitivities (e.g., Barlow 1957; Rushton 1965d; Boynton and Whitten 1970; Enroth-Cugell and Shapley 1973; Dowling and Ripps 1972; Dowling, Green, Ripps and Siegel 1973; Hood and Hock 1975)[10, 287, 45,87,84,33,147]. In addition, a number of experiments involving chromatic after-effects associated with spatial and temporal characteristics of stimulation and with efferent responses such as eye movements, appear to have their origins in the striate cortex or at least higher levels than retinal (e.g., Kohler 1962; McCollough 1965)[209,247].

In short, there is ample evidence to suggest a system in which adaptational effects take place at a number of levels throughout the visual mechanism. Nonlinearities and interactions abound in the visual pathways. From this alone it is clear that a quantitative description of the dynamics of chromatic adaptation may be difficult to formulate. As with colorimetry in general, however, the difficulties can be somewhat reduced if we consider only conditions of equality. It may be assumed that an invariance of equal neural signals, however they may have arisen, represents a condition of equal color response and vice versa. With this simple but parochial assumption, it is possible to examine chromatic adaptation from the standpoint of response equalities. That kind of examination is what is meant by the phrase 'chromatic adaptation theory'.

Chromatic adaptation theory.

Ordinary color matching that forms the basis of colorimetry may be described as 'symmetric' matching. Two stimuli are presented to the same or nearly the same portion of the retina(e) of one or both of an observer's eyes at the same or very nearly the same time. The conditions of such a match are said to be symmetric since all spatial, temporal, and physiological factors involved in the match are the same. In the notations of colorimetry, the match is conventionally represented as:

$$\begin{aligned}
X &= k\left\{\int\rho(\lambda)_1\cdot H(\lambda)\cdot\bar{x}(\lambda)\cdot d\lambda\right\} = k\left\{\int\rho(\lambda)_2\cdot H(\lambda)\cdot\bar{x}(\lambda)\cdot d\lambda\right\} \\
Y &= k\left\{\int\rho(\lambda)_1\cdot H(\lambda)\cdot\bar{y}(\lambda)\cdot d\lambda\right\} = k\left\{\int\rho(\lambda)_2\cdot H(\lambda)\cdot\bar{y}(\lambda)\cdot d\lambda\right\} \quad (1) \\
Z &= k\left\{\int\rho(\lambda)_1\cdot H(\lambda)\cdot\bar{z}(\lambda)\cdot d\lambda\right\} = k\left\{\int\rho(\lambda)_2\cdot H(\lambda)\cdot\bar{z}(\lambda)\cdot d\lambda\right\}
\end{aligned}$$

where: λ = wavelength

H = irradiance

ρ = reflectance (or transmittance)

$\bar{x},\bar{y},\bar{z}$ = spectral distribution coefficients

k = normalizing factor

1,2 = samples

X,Y,Z = tristimulus values.

Using functional notation, Equation 1 can be more economically represented as the identity:

$$\begin{aligned} g_1(X,Y,Z;A) &\equiv g_1(X,Y,Z;A) \\ g_2(X,Y,Z;A) &\equiv g_2(X,Y,Z;A) \\ g_3(X,Y,Z;A) &\equiv g_3(X,Y,Z;A) \end{aligned} \tag{2}$$

where X,Y,Z represents a tristimulus specification, A refers to the illuminant, and the identity of terms is obvious.

Stiles (1961)[322] has detailed the theoretical differences between the symmetric case represented by Equation 2 and the 'asymmetric' case where an identity of terms does not obtain between the conditions of a color match. We may assume, for example, that by some means a color match is obtained for stimuli that are imaged on the same rod-free, foveal area of the retina under two different conditions of illumination to which the observer is adapted. Then the functional notation for such a match - a match that is asymmetric over illumination and consequent visual sensitivities - may be written as:

$$\begin{aligned} g_1(X,Y,Z;A) &\xrightarrow{\Xi} g_1(X',Y',Z';A') \\ g_2(X,Y,Z;A) &\xrightarrow{\Xi} g_2(X',Y',Z';A') \\ g_3(X,Y,Z;A) &\xrightarrow{\Xi} g_3(X',Y',Z';A') \end{aligned} \tag{3}$$

Equation 3 represents an equality condition rather than an identity. That is, a correspondence, Ξ , exists in terms of the criterion of matching color appearance. Since the stimulus terms of Equation 1 (ρ and H) are not the same on both sides of the equation when adaptation is to different illuminants, the tristimulus values and illuminant terms of Equation 3 are necessarily different. Those differences are indicated by the prime superscripts. Depending upon the factors responsible for these asymmetries, the color match may or may not be transitive in the same sense that a symmetric match is said to be transitive according to the 'laws of color mixture' (Grassman 1853, 1854)[116,117]. That is, if stimulus 1 specified as X,Y,Z under condition A matches stimulus 2 as

X',Y',Z' under condition A' and, further, if stimulus 2 also matches a third stimulus specified as X",Y",Z" under A", then by the equivalent of algebraic substitution we assume that X,Y,Z under A will also match X",Y",Z" under A". Such substitutional relations are what is meant by transitivity.

When two different stimuli, corresponding to two different adaptation illuminants, are used to stimulate the same foveal area on temporally distinct occasions (e.g., a match involving memory) the conditions that satisfy requirements for transitivity are the same as in the symmetric case. However, if the asymmetry is compound in the sense that, in addition to different illumination, different parts of the retina or different eyes are stimulated, then the A' term of Equation 3 represents a plural set of parameters and there is no a priori basis for assuming that transitivity of the match will obtain. Whenever there are interactions between conditions A and A', the match is not independent. This is a consequence of the fact that asymmetric sensitivity interactions require nonlinear rather than linear transformations for conversion, thereby destroying the substitutional characteristic referred to as transitivity (e.g., Wyszecki and Stiles 1967)[373]. This may pose problems for interpreting data from chromatic adaptation studies that involve presentation of stimuli to different parts of the same eye or to different eyes of the same observer.

Two other 'laws' of (symmetric) color matching may also influence the ease of interpretation of data derived from asymmetric matches. These are what have been called laws of additivity and proportionality. In symmetric matching what is meant by additivity is that if two stimuli A_1 and B_1 provide a color match, and two other stimuli A_2 and B_2 also match, then $A_1 + A_2$ will match $B_1 + B_2$; when the stimuli are self-luminous and their irradiances are what is added. A corollary, known as proportionality, states that for any positive factor, a, the conditions aA_1 will match aB_1 as long as A_1 and B_1 match in color.

If additivity and proportionality hold for asymmetric color matches, then the two sets of tristimulus values denoting the match (X,Y,Z and X',Y',Z') between conditions A and A' will be related by a linear transform matrix ξ :

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \xi_{AA'} \begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} \tag{4}$$

Wyszecki (1954a)[368] has provided a graphical solution for Equation 4 that aids in visualizing its implications in terms of CIE chromaticity relations. A similar graphical interpretation was also described by Bouma and Kruithoff (1947)[34]. The relationships apply to any pair of illuminants and to any likely set of three independent primaries of which the CIE primaries are some linear transform. The essential features of such a transformation are the assumptions of (a) linearity, and (b) invariance of a set of three fundamental primaries. The history of these two assumptions goes back about one hundred years.

Helmholtz (1866)[126] suggested that as a consequence of what he called 'fatiguing' of the 'nervous substance' of the eye with prolonged exposure to illumination, there occurs a selective decrease in the sensitivities of these substances. This concept was adopted a few years later when von Kries undertook to study the process of adaptation. Apparently he first considered and then rejected the idea that chromatic adaptation could be explained by addition of 'after-image light' to sensations (q.v., Jameson and Hurvich 1972)[183]. He then went on to develop a quantitative expression for the fatigue notion of Helmholtz (von Kries 1877,1904,1905,1911; v., MacAdam 1970)[213-216,235]. Von Kries' crucial statement, translated, reads: "Different composed stimuli, which look equal for the nonfatigued eye, will also look equal for the somehow fatigued eye" (Terstiege 1972)[328]. In other words, the equivalent of the metamer rule of Grassman applies over adaptationally asymmetric matches. Thus, metameric color matches are assumed to be independent of chromatic adaptation. This assumption has come to be known as the 'persistence law'.

That law implies that sensitivities of the adapted visual mechanism are simply proportional to the sensitivities of the mechanism under some different condition of adaptation. Thus, we have the relationship for which von Kries is most well known; the von Kries coefficient law:

$$\begin{aligned} s'_1 &= k_1 s_1 \\ s'_2 &= k_2 s_2 \\ s'_3 &= k_3 s_3 \end{aligned} \qquad (5)$$

where s_i may be considered the neutral (or rest-state) sensitivities and s'_i are sensitivities altered by exposure to illumination. The coefficients k_i are taken to be inversely proportional to the relative strengths of activation by the spectral power of illumination.

Unfortunately, it has not often been noted that von Kries was far from dogmatic in stating his coefficient law. He was careful to point out that the proposal was intended only as a first-order approximation that would "offer preliminary orientation in a field that at first seems completely incomprehensible... (in order to) direct research into a correct course" (v., MacAdam 1970)[235]. Starting with this caveat, von Kries derived a quadratic expression for general transformation of sensitivities over variations in illumination. He recognized that to preserve the integrity of the rules of color mixture, it was necessary that solutions to the quadratic equations yield only three real root-pairs. There must only be three invariant points: "for if we set the condition that three definite points of the color chart are to be invariable, and if we, for those points, fix the effect of adaptation as an apparent change of quantity by a coefficient, thereby the whole system of adaptation-shifts is determined in such a manner that no other points can remain unshifted" (op. cit.). He thus recognized that a critical test of his hypothesis would be "to establish whether such invariable points can be found and, if so, what can be found regarding their number, the constancy of their position, etc."

We see, then, that from the beginning the validity of Equations 4 and 5 could be subjected to test by determining the number and stability of the underlying fundamental primaries. Theoretically, it is possible to deduce these fundamentals from asymmetric matches of three or more stimuli over variations in two or more conditions of chromatic adaptation. In practice most such experiments have involved more than the theoretical minimum of three stimuli to normalize the influence of random error on determination of the transformation matrix. It is not quite so common, however, that more than two illumination conditions have been used in any one experimental investigation.

A number of mathematical and statistical techniques have been used to determine the transformation matrix $\xi_{AA'}$. Wyszecki and Stiles (1967)[373] have summarized the salient features of the methods. For the matrix to be linear with three invariant, real roots, there are two basic conditions that must be met. These are (1) validity of the metamer rule for asymmetric matches; i.e., the persistence law must hold, and (2) the proportionality law must hold; and if that is so then the additivity law will also be true.

Results of several physiological investigations may be marshalled to examine the question of validity for the persistence law. Basically, the question is whether or not there are three sensitivity functions for chromatic vision that are each independent.

Existence of three cone photopigments has been verified (e.g., Rushton 1963a,b,c, 1965a,b; Rushton and Baker 1963; Rushton and Henry 1968; Naka and Rushton 1966; Brown and Wald 1964; Marks, Dobelle and MacNichol 1964)[281-285, 288,289,251,57,243]. The question of independence has been examined in a number of ways. Wald used psychophysical increment threshold techniques to provide data for comparison with his earlier work on photochemical selective bleaching of receptor pigments (e.g., Wald 1937; Wald, Brown and Smith 1955)[345,346] and found a lack of independence. However, the bleaching flux used for adaptation was of a very high level; so high as to be well within the range where, even for symmetric matching, metamerism is found to break down (Burch 1898; Wright 1936; Brindley 1953; Terstiege 1967)[58,361,53,327]. In addition, interpretation of increment threshold data such as that derived by Wald may be somewhat confounded by the fact that, apparently, detection of a change may occur if the test flash exceeds the threshold of either the chromatic or the achromatic response system (King-Smith and Carden 1976)[205]. However, data obtained with the Stiles-type increment thresholds, involving analysis over a broad range of adapting intensities, also shows a lack of independence (Stiles 1949,1959; Boynton, Ikeda and Stiles 1964)[320,321,43]. In addition, a psychophysical experiment involving mixed adapting stimuli (Boynton, Das and Gardiner 1966)[44] similarly leads to the conclusion that there are interactions among the photopic visual mechanisms for chromatic adaptation. Finally, it may be noted that Dimmick and Wienke (1958)[81] showed a breakdown of metamers with only moderate variation in chromatic adaptation. Thus, the experimental evidence at hand does not support the hypothesis of independence for three sensitivity functions.

If the persistence rule is not valid we would not expect the proportionality rule to hold either. However, if the persistence rule is nearly correct at some moderate levels of chromatic adaptation, then there also exists a possibility that proportionality may have some first-order approximation to validity. There are at least two kinds of information that may be brought to bear on this question. The first involves a direct approach to measure proportionality over adaptationally asymmetric matches. The second, which provides by far the greatest body of data, is an indirect approach in which an attempt is made to determine the fundamental sensitivities according to the method of Equation 4 above.

Hurvich and Jameson (1958)[165] approached the problem directly. Using a haploscopic asymmetric method (i.e., differential adaptation of an observer's two eyes and subsequent interocular comparison of stimuli), they produced color matches for six different stimuli over adaptation illuminants of greatly different chromaticities and illuminances within the photopic range. The resultant matches were far from constant in chromaticity over stimulus luminance; as should have been the case if the proportionality rule obtained. Hunt (1949, 1950, 1952, 1953)[152-155] has also provided haploscopic matching data in which the same kinds of discrepancies are found over much smaller variations in adaptation. From these experiments alone, it is clear that proportionality does not hold for adaptationally asymmetric color matches when stimulation is confined to the rod-free foveal area of the retina at moderate to low intensities of illumination.

The indirect evidence regarding proportionality comes from a variety of experiments where attempts were made to deduce fundamental sensitivity functions from adaptational metamers. Many experiments of this kind have been conducted (e.g., Wright 1934,1937,1946; Noteboom 1935; Burnham, Evans and Newhall 1952,1957; Helson, Judd and Warren 1952; Kellersohn 1955; Wassef 1958,1959; MacAdam 1956,1958,1961,1963; Wassef and Aziz 1960; Scheibner 1963,1966; Wagner 1969; Sobagaki, Yamanaka, Takahama and Nayatani 1974; Sobagaki, Takahama, Yamanaka, Nishimoto and Nayantani 1975)[360,362,364,258,60,61,138,204,352,353,231-234,354,295,296,344,305,306] but nearly all who have attempted to solve for the transformation matrix have failed to avoid complex roots. The implication would then be that either there are more than three fundamentals or, if three in number, they are not independent. Some of these experimenters have resorted to ad hoc assumptions, some have made arbitrary adjustments to the data, and others have imposed restraints of various kinds in order to derive approximate solutions that accord with the postulates of the linear von Kries transform. Alternatively, when the von Kries model has not been imposed, empirical transformations have been more complex than the relations implied by the linear model. In short, there is not a good basis in experimental fact for strict validation of the von Kries coefficient law. Despite this, its use persists; perhaps because of the appealing simplicity of the model and the fact that it does yield rough approximations of the general trends of adaptation-induced color shifts.

Several alternatives to the von Kries model have been proposed either directly or indirectly. They include empirical transforms (both linear and nonlinear), nonlinear transforms based on theoretical considerations, and theoretical multi-stage models, together with a number of other proposals that are less clearly defined.

The von Kries coefficient rule of Equation 5 shows modified sensitivity as a proportion of original sensitivity. An alternative proposed by Steffen (1955)[310] suggests that the proportional relation be instead between logarithms of sensitivity. MacAdam (1961, 1963)[233,234] proposed that sensitivities are related through power transforms. That proposal was the result of a 'curve-fitting' analysis adopted to avoid the assumption of five or six fundamentals (MacAdam 1956)[231] or an unorthodox theory of color vision that would deny the existence of metamers even for symmetric matches (MacAdam 1958)[232]. Burnham, Evans and Newhall (1957)[61] used a linear transform, based on an analysis of Brewer (1954)[50], which effectively introduced a non-zero ordinate term in Equation 5. This least squares determination was also an empirical representation of their data.

Hunt (1950)[153] proposed a nonlinear relationship, later developed in quantitative form by Takahama, Sobagaki and Nayatani (1975)[324], based on an assumption of variable interaction among chromatic neural signals as a function of level of stimulation. In his experiments, Hunt (1950,1952,1953,1958)[153-156] noted a level-dependence of asymmetric haploscopic matches and he reasoned that such results could not be expected from a simple, linear relationship involving proportionality. He proposed as a possible explanation, that there are proximal interactions among chromatic signals from three receptor-types that are active at low levels of stimulation and become increasingly inactive as stimulation level increases. The net result would be that effective sensitivities of the chromatic response process are spectrally broad at low levels and narrow at high levels of stimulation. It is of interest that Sloan (1928)[304] found such a change in the photopic luminous efficiency functions she measured in her heterochromatic brightness matching experiments; but it is not clear whether these results stemmed from effects of cone additivity or non-linear interactions. It should also be noted that Hunt's hypothesized variation in spectral bandwidth is opposite in form to that expected from consideration of photo-pigment 'self-screening' (e.g., Brindley 1970)[55] where broadest bandwidths should be found for higher levels of stimulation. In any event, the proposed nonlinear relationship does account in principle for observed discrepancies in multi-level asymmetric color match data; although Takahama et al (1975)[324] found that predictions based on the model were not greatly different from those of the Burnham et al (1957)[61] empirical linear model when treating adaptation shifts from CIE Illuminants D_{65} to A for stimuli such as those used in the CIE Colour Rendering Method.

Jameson and Hurvich (1972)[183] have offered a 'two-process' interpretation for chromatic adaptation. Their qualitative model involves initial coefficient adjustment of three sensitivities followed by an additive or incremental adjustment to opponent chromatic response. Simply stated, the alteration of component sensitivities leads to a change in both shape and base-line (or bias level) of spectral opponent response functions. These response increments are not the same for each of the response functions. The opponent functions themselves may be nonlinear (e.g., Larimer, Krantz and Cicerone 1975)[224]; a possibility admitted by Hurvich and Jameson (1960, 1961; Jameson and Hurvich 1961, 1972)[166,167,180,183]. The proposed model thus has a number of degrees of freedom. It has not yet been subjected to systematic quantitative study.

J. Walraven (1976)[349] has suggested that the response increment stage of the Hurvich-Jameson model "appears to be of such a surprising simplicity that only a slightly modified version of the von Kries coefficient law may... suffice" (op.cit.). He points out that the proportionality rule conflicts with Kirschmann's (1891)[206] third rule of color contrast (i.e., color contrast is maximum when achromatic contrast is minimum) so that account should be taken of that part of the total response which is common to both sample and surround before a proportionality coefficient is applied to adjust sensitivities. In other words, the <u>difference</u> between a sample and its surround may follow the coefficient rule. However, the single experiment on which Walraven's proposal is based involved only test stimuli that were more intense than their surrounds; by ratios of up to about 4.3 times in retinal illuminances. However well the data may apply to chromatic induction, there is no a priori basis for considering them to describe chromatic adaptation since the surround did not completely control the observer's adaptation.

Richter (1976)[276] offers another variation on the two-stage model. He would add a response increment to the opponent chromatic response, but it is the increment which is varied according to a coefficient rule. The primary reason for not applying different multiplicative factors to the first stage of response derives from Pointer's (1974)[269] work showing that small color differences are invariant over adaptation; thus, the equation for color differences should contain coefficients that do not vary with adaptation. Richter's model is based in large part on his own haploscopic experimental data (Richter 1975; Richter and Nicolaisen 1975)[275,277] and is capable of providing an excellent simulation of the Munsell Renotation spacing of color appearances under CIE Illuminant C. In common with the von Kries model, Richter's predicts that only three points in a chromaticity diagram - points corresponding to the three fundamental primaries - remain invariant over adaptation. All other points must change chromaticity to satisfy the model's predictions for adaptational metamers. This requirement conflicts with some theoretical expectations (Hurvich and Jameson 1951b,1954,1958)

[162,163,165] and with experimental findings (Larimer, Krantz and Cicerone 1974,1975; Cicerone, Krantz and Larimer 1975)[223,224,66] for dominant wavelengths of near-spectral stimuli eliciting unique hues over variations in chromatic adaptation.

In one sense, the incremental response concept is reminiscent of the idea of 'discounting the illumination' put forward in the last century (Helmholtz 1925, 1962)[128,129]; although Hurvich and Jameson have made clear that the incremental part of their model taken alone is no more effective for describing chromatic adaptation than is the coefficient rule alone. None-the-less, the idea of discounting the illuminant has been espoused by some vision workers (e.g., Judd 1940; Evans 1974)[186,93] and with variations by the Gestalt psychologists Gelb (1929)[109], Katz (1935)[203], and Koffka (1935)[207]. Of these, only Judd (1940,1960)[186,188] has offered a quantitative structure for prediction and that is generally more appropriate to chromatic induction than to chromatic adaptation.

Helson (e.g., 1964)[135] has developed an 'adaptation-level theory' which accounts mainly for phenomena that have variously been described under the rubrics 'color constancy' (Helmholtz 1866; Jaensch 1921; Haack 1929)[126,173,120], 'color level' (Koffka 1935)[207], 'color transformation' (Jaensch and Müller 1919)[174], and 'color conversion' (Helson 1943)[133]. Helson hypothesizes some neutral point, described by an algebraic combination of logarithms of stimulus attributes, which exists for any condition of adaptation. That neutral point is the 'adaptation-level' according to Helson, and all color perceptions arise as a result of gradient relations to it. Quantitative expressions for these relations are provided by Helson (1964)[135].

The constancy of stimulus proportionality implied by such models is also central to Land's (1964)[221] 'retinex' theory of color vision developed from his work on color perceptions in complex fields (Land 1959, 1962)[219,220]. Woolfson (1959)[358] analyzes Land's results in terms of discounting the illumination, but others place a different interpretation on them (e.g., Walls 1960; Judd 1960; Belsey 1964; Pearson, Rubenstein and Spivak 1969)[348,188,27,264]. Land and McCann (1971)[222] have adopted a stimulus-oriented view of the problem, later developed more fully for chromatic perception by McCann and co-workers (McCann, McKee and Taylor 1976)[246], in which proportionality of stimulus elements according to 'red, green and blue impressions' is computed from cascaded border ratios of intensity. We are told by McCann et al (vide supra) that they will publish a comparison of their predictions with other theories of chromatic adaptation. A complete understanding of their proposals awaits such further details.

There are, then, a number of alternatives to the von Kries linear coefficient law for modelling the process of chromatic adaptation. Some of these are more satisfactory than others in the sense of providing unequivocal agreement with presently known facts of physiology and according to their ability to yield quantitative predictions. Ultimately, the appropriateness of any model will be determined by the extent of its agreement with the physiological facts of color vision; when they are known with sufficient certainty. Until that time, the test of any model will be its ability to predict satisfactorily the results of experimental studies of chromatic adaptation. Accordingly, the methods and data of various experimental techniques for studying chromatic adaptation are of considerable interest since it is these which offer measuring sticks with which to evaluate models and theories of chromatic adaptation.

Psychophysical studies of chromatic adaptation.

Chromatic adaptation has been explored rather extensively; probably because of the dual interest in color vision theory and in practical application of data that might offer a solution to the prediction problem. If we consider only those experiments aimed at elucidating a transformation method, as opposed to those that have been primarily physiological in thrust, the investigations seem to fall into several classes. Table I has been constructed to illustrate this point.

Principal experiments (identified by senior author and date of publication) are most generally classed in two ways: (1) according to the kind of stimulus presentation used, and (2) in terms of the experimental method used for study. The form of stimulus presentation is further subdivided into two broad categories: (a) simple fields, and (b) complex fields. In turn, each of these subdivisions consists of a number of groupings described by modes of color appearance or complex stimulus presentation modes. The experimental methods are classed as four techniques of gathering data: (1) direct scaling, (b) differential retinal conditioning and comparison, (c) differential ocular conditioning and comparison (haploscopic matching), and (d) memory matching. Since a number of additional works of interest do not lend themselves to this kind of categorization, Table II has been prepared to list some publications that may better be described as general or theoretical in nature.

In many cases of what have been arbitrarily classed here as general or theoretical publications, experimental data (usually obtained from other works) is examined in some detail. Further evidence of the arbitrary nature of any such classification system may be taken from the fact that all experimental reports delve into theory and some include more than one experimental method. Never-the-less, I have tried to group the works according to their primary emphases. I believe this undertaking is justified to the extent that it may be seen rather easily where most work has been done and, conversely, where little or no investigation has been carried out.

Table I reveals that some combinations of stimulus presentation and experimental method have been used much more extensively than others. For example, it is immediately clear that haploscopic matching, suggested by Hering (1964, pp.244-245,256,259)[145], has found the most frequent use. At least two nineteenth century workers (Schön 1874; Voeste 1898)[301,343] used the method that relies on adaptation of different portions of the retina, but that method has been used only once in re-

Table I

Classification of Adaptation Studies

Simple Fields:

Method	Surface Mode	Aperture Mode
Direct Scaling	Sobagaki 1974,1975 Pointer 1975	Boynton 1956 Rowe 1972
Memory Matching	Helson 1938,1940, 1947,1948,1952, 1956 Judd 1940 Kruithof 1942,1955 Bartleson 1966	
Differential Retinal Conditioning		Schön 1874 Voeste 1898 MacAdam 1956
Haploscopic	Noteboom 1935 Barr 1952 Burnham 1957 Hunt 1965 Eastman 1972	Wright 1934,1937, 1946 Walters 1942 Hunt 1950,1952, 1953,1968 Burnham 1952,1959 Fry 1955,1958,1964 Jameson 1956,1961 Wassef 1959,1960, Scheibner 1963 Richter 1974,1975 1976 Terstiege 1967 Wagner 1969 Valberg 1974,1975

Complex Fields:

Method	Luminous Images	Projected Images	Reflection Images
Direct Scaling	Pearson 1969	Evans 1943	Bartleson 1958
Memory Matching			
Retinal Conditioning			
Haploscopic			Bartleson 1966

cent years (MacAdam 1956)[231]. Memory matching has been largely confined to stimulus presentations in the surface mode of appearance; in large part because collections of material color standards are most readily available in that form. Only recently has direct ratio scaling enjoyed much popularity. Very little work has been done

Table II

General, Theoretical, and Review Studies of Chromatic Adaptation

General and Theoretical:

Balcon 1970
Boynton et al 1965, 1966
Brewer 1954
Burnham 1959
Gellhorn & Fabian 1926
Helmholtz 1866
Hering 1888
Hunt 1949, 1958
Ingling and Drum 1973
Kellersohn 1955
von Kries 1877, 1904, 1905, 1911
MacAdam 1949, 1955, 1961, 1963
Münch & Schultz 1967
Nickerson 1963
Noddack & Jarczyk 1955
Ouweltjes 1966, 1970
Pointer 1974
Sanders 1955
Scheibner 1966
Speelman & Krauskopf 1963
Stiles 1961
Thomas et al 1961
Tschermak 1941, 1952
J. Walraven 1976
P. Walraven et al 1966
Wassef 1958
Wright 1944, 1946
Wyszecki 1954a

Reviews:

Graham & Brown 1965
Jameson & Hurvich 1972
Terstiege 1972
Wyszecki & Stiles 1967

with complex stimulus arrays and by far the greatest effort seems to have gone into studies of simple, aperture mode, stimulus arrays addressed by the haploscopic method.

Detailed inspection of the references cited in Tables I and II reveals, in addition, that not very much work has gone into the study of chromatic adaptation effects involving systematic covariation of illuminant quality with both luminance factor and illuminance.

In many cases only single levels were used for each of these additional parameters. In a disconcertingly large number of cases variations in more than one factor have been pooled; thereby confounding results and making interpretations difficult. With the exception of direct scaling experiments, almost all studies have been limited to an attempt to specify adaptational metamers. None of the experiments have attempted to map color relations in three dimensions of color space for a plurality of attributes of color appearance over covariations in illuminant quality, luminance factor, and illuminance.

There is, then, a plethora of data that relate to only a portion of the total problem of color appearance variation with adaptation. There is information relating to stimulus conditions for equality of color appearance on a plane of the color solid but very little that can be used to describe the way color appearances themselves change when chromatic adaptation is varied.

In order to gain some insight into typical methodology of experimentation used to study chromatic adaptation, three different approaches will be considered in the following paragraphs. These are what have been labeled: (1) memory matching, (2) haploscopic matching, and (3) direct scaling.

A classic experiment, usually described as memory matching, is that of Helson, Judd and Warren (1952)[138]. Those workers scaled the relative attributes of hue, saturation and lightness of 60 Munsell reflecting samples illuminated with 2 sources of approximately 6,700 K (kelvins) and 2,854 K. The attributes scaled are referred to as 'relative' because two end-point anchors were used for each of the scales (v. Bartleson 1976)[19]. Both lightness and saturation were scaled on what was described as an 11-point scale running from 0 to 10. However, observers were permitted to use values with increments of one-half and one-quarter, so the scale was effectively a 44-point one. Hue was divided into 36 categories of hue name: 8 names for hues intermediate between each pair of unitaries (red, green, blue and yellow) inclusive of end-points.

In terms of information theory, the observers were asked to remember and identify about 5.0 'bits' for hue and 5.5 for each of lightness and saturation; where 'bits' are defined as the logarithms to the base 2 of the number of categories. This requirement approaches the common limit of about 6 bits of information transfer capacity for the normal observer (e.g., Attneave 1959)[4].

Thus, the scaling method was one of interval scaling. The scaling criterion is what has been the basis for referring to the experiment as memory matching. Observers were trained to respond according to intervals of Munsell Hue, Value, and Chroma; although four primary hues were used instead of the five Munsell primaries, Munsell Chroma was called 'saturation', and Value was called 'lightness'.

A group of 9 observers was trained for a total of 8 hours to recognize Munsell samples and correctly identify them according to the scale values used in the experiment. The 6 'best' observers were selected for the experiment. 'Best' was defined in terms of ability to provide consistently correct identification to within one unit of Munsell notation. According to Helson et al: "that memory played some part in the final estimates cannot be denied, but a naive, phenomenological approach was encouraged during the final observations" (op.cit., pp.222-223)[138]. In substance, then, the experiment used category scaling involving at least some element of long-term memory.

The stimuli were 1 by 1 inch in size. If normal viewing distances were used, they would have had a visual subtense of about 1^{o} to 4^{o} and "they were placed a few inches apart on a shelf in the booth and 11 were exposed in random order during each observation" (op. cit., p.224)[138]. The viewing booth was "a light-tight booth lined with a good non-selective cardboard throughout" (op.cit., p.223)[138]. The stimuli were arrayed against each of three different backgrounds (of unspecified subtense) having reflectances of 3, 21, and 78 per cent. Illuminances were 73 footcandles (approximately 785 lux) at 6,700 K and 57 footcandles (613 lux) at 2,854 K. According to the authors: "the difference of about 28 per cent between the two types of illumination being studied is not great enough to be responsible for the color difference observed... previous studies have shown that it takes changes in illumination levels of the order of 100 to 1 to cause appreciable shifts in hue under the conditions of this study (Helson and Jeffers 1940)[137]" (op.cit. p.224).

The results of the Helson et al experiment may be summarized by saying that hue and saturation shifted with chromatic adaptation by different amounts according to color temperature, illuminance, and luminance factor. Unfortunately, many of the data were pooled so that the individual effects of these factors are not systematically explicit in the results. Hue shifts tended to be larger than shifts in saturation. The largest shifts were found with variations in illuminant chromaticity and luminance factor. Apparently, the quasi-memory method was satisfactory as an experimental technique. However, it taxed the information channel capacity of the observers and required both training and selection.

It should be noted that whenever memory is involved in an asymmetric color match, one must recognize the possibility of bias or distortion arising from the memory trace itself. Relatively short-term memory associated with color appearances of abstract forms has been shown to yield systematic distortions (Newhall, Burnham and Clark 1957)[254]. Saturation tends to increase with memory and lightness increases for light colors and decreases for dark colors. When complex fields are used, with the accompanying possibility of perceiving stimuli as familiar objects or their images, the process of memory-color, as distinct from color memory, may also intrude (Hering 1964)[145]. Memory-color is distinguished from sheer ability to remember colors by the presence of clues to distinctive color attributes associated with objects that are familiar through experience (Bartleson 1960)[13]. Typical memory traces of the two processes have been compared and it was found that non-monotonic hue shifts occur in memory-colors in addition to the monotonic saturation and lightness variations of simple color memory (Bartleson 1961)[14]. In substance, then, a color match over time is apt to be biased or distorted. A general discussion of the role of memory in judgments is given by Sandusky (1974)[294].

The haploscopic method of experimental study does not rely substantially on memory. It involves presentation of independent stimuli to each of an observer's two eyes in order that he may make an interocular comparison. Hering (1874,1964)[143,145], Abney (v. Burnham et al 1957)[61], Hecht (1928)[121], and Schouten and Ornstein (1939)[302] number among the well-known experimenters who have used the haploscopic technique. But perhaps the most often cited experiments of this kind are those of Wright (1934,1937,1946)[361,362,364]. He pointed out that a critical assumption of the method relates to independence of the two ocular channels. That is, to what extent does stimulation of one eye influence the sensitivity of the other eye? In Wright's experiments the extent of any such interactions tended to have a much smaller effect on appearance than that brought about by differences in adaptation. It is largely because of this that it has usually been assumed that the two eyes are essentially independent with respect to sensitivities.

However, a number of workers have pointed out that an observer's two eyes are not completely independent (e.g., Hecht 1928; Tschermak 1952; Thomas, Dimmick and Luria 1961)[121,340,330]. In addition, there are differences between any observer's two eyes. Some of these differences and interdependencies can be compensated or normalized. For example, differences in inherent sensitivities may be normalized by correction according to data obtained from quasi-symmetric matches; haploscopic matches for the same conditions of interocular adaptation (e.g., Hunt 1950; Burnham et al 1952)[153,60]. When the natural pupil is used, data on consensual pupil responses with and without interocular illumination disparities may be used for correction of retinal illuminances (Bartleson 1968a)[16]. But many of the differences and particularly the interactions between an observer's two eyes cannot be corrected. Physiological evidence shows that, at least for some animals, only a portion of the cortical cells (Hubel and Wiesel 1968)[151] and geniculate axons (Jung 1961)[191] are capable of responding to both monocular and binocular stimulation; and such cells apparently provide binocular summation and inhibition. In the realm of psychophysical results there are threshold experiments concerned with brightness perception that indicate binocular interactions (e.g., Matin 1962)[245]. There is also some evidence that sensitivity interactions occur which would intervene most seriously when interocular images are of the superimposed kind (Paris and Prestrude 1975)[263]; i.e., where corresponding retinal areas are each stimulated in common. In addition, chromatic threshold interactions have been reported (Helms and Prehn 1958; Helms and Raeuber 1958)[130,131] and inhibition from binocularly presented inducing fields has been measured for suprathreshold conditions of stimulation as well (Alpern and David 1959; Mackavey, Bartley and Casella 1962; Thomas 1963; Fiorentini and Radici 1958)[2,236,329,100]. Bartleson (1966)[15] has used a memory matching technique to measure the change in perceived color of a constant-stimulus reference field with variations in retinal illuminances presented to opposed eyes and found that reasonable constancy obtains only over a range of interocular disparities of slightly less than two log units; not much different from the figure of 100 to 1 found by Helson and Jeffers (1940)[137] for significant shifts in color appearance with illuminance. Valberg (1975)[342] has also noted the limited range of permissible interocular luminance disparity for constant saturation in haploscopic color matching.

These problems are recognized by most experimenters and some have taken whatever steps may be possible to minimize interactions in haploscopic matching. Several variations in methodology have been proposed. Using some preliminary experiments (Barr, Clark and Hessler 1972)[11] as a point of departure, Eastman and Brecher (1972)[85] examined both adaptive and nonadaptive haploscopic matches and, as a consequence of their findings, proposed an alternating intermittent scheme for viewing sample and comparison fields. Similar proposals were made in 1961 by a panel of the British National Illumination Committee and were used in a colorimeter degign by Hunt (1965)[157]. Care has generally been taken to superimpose the test field over a maximally black area where alternation has not been used. In some cases uncontrolled alternation has been used in a design which superimposes the entire field of one eye on a black background during comparisons (e.g., Bartleson 1966; Breneman 1966)[15,47].

Despite the problems of haploscopic matching, the bulk of adaptation studies have been conducted with that experimental method. The information derived from these experiments has contributed significantly to our knowledge of the factors affecting color appearance.

Burnham, Evans and Newhall (1952,1957)[60,61] used the technique and did make corrections for interocular sensitivity differences. They also minimized luminance disparity by maintaining the same adapting luminance for both eyes. Earlier, Hunt (1950)[153] had made such corrections in studying changes with chromatic adaptation. He also used the haploscopic method to examine adaptation-dependent changes in both small and large stimuli (Hunt 1952,1953)[154,155] together with changes brought about by luminance factor (Hunt 1953)[155] and illuminance (Hunt 1958,1965)[156,157].

Burnham et al investigated adaptational metamers for 12 samples, presented in the surface mode of appearance, under 3 conditions of illumination: CIE Illuminants A and C and a 'green' illuminant. Test stimuli subtended 1° by 2° visual angle for each eye; providing a binocularly fused bipartite image of 2° on a side. The surround was 40° with a luminance of 25 footlamberts (approximately 86 cd$\cdot$m^{-2}), The stimuli were divided into three groups of four each at luminance factors of 0.59, 0.30 and 0.12. Both test and matching stimuli were produced by a colorimeter field and were independent of the adapting illumination. After a 3 minute adapting period the test and matching stimuli were presented for 0.3 second followed by a period of 0.7 second in which they were replaced by a continuation of the surround. The cycle was then repeated until a satisfactory match was obtained. The 3:7 alternation ratio was determined to be adequate for stable adaptation. It was also found that reducing the alternation ratio to as little as 6:94 provided no further increase in stability of adaptation.

Both individual data of the 4 observers and their pooled results showed similar color shifts with adaptation. Large shifts were found in both hue and saturation. The average results were characterized by an empirical linear matrix; the form of which was not consistent with the von Kries coefficient rule. Predictive error of the matrix was from 1 to 3 per cent for luminance. Chromatic errors with replicate matches were said to be "several times" as large as the predictive errors of about 0.007 to 0.010 in CIE 1931 chromaticity coordinates. By comparison, Bartleson (1966)[15] reported that unit standard deviation ellipses of haploscopic matching were approximately ten times as large as MacAdam's (1943)[228] variability ellipses for symmetric, monocular, color matching.

In addition to studying changes in color appearance matches with adaptation to illumination, Hunt has used the haploscopic method to examine adaptation-dependent changes for both small and large test stimuli, the influence of luminance factor, and of illumination (Hunt 1950,1952,1953,1958,1965)[153-157].

In his experiments involving variations in luminance factor, a 60° surround was used with a centrally located 1° test field. Surround luminance was constant at about 75 trolands (corresponding approximately to 8 $cd\cdot m^{-2}$) and the test stimuli ranged from 0.7 to 6,300 trolands (about 2 to 1,024 $cd\cdot m^{-2}$); i.e., from 1/4 to 128 times the surround level. He found very large changes in excitation purity of the match as a function of luminance factor; purity increased as relative luminance increased. Similar results were obtained for 20° test fields except that the extent of color shift was somewhat smaller. These findings have been reinforced by subsequent data for both saturation and lightness (e.g., Hurvich and Jameson 1960,1961; Jameson and Hurvich 1959,1961,1964; Bartleson 1966; Bartleson and Breneman 1967a,b; Pitt and Winter 1974; Valberg 1975)[166,167,179-181,15,20,21,266,342].

Hunt's illuminance studies used levels ranging from near zero to 100 footcandles (about 1,076 lux). Again, saturation was found to be highly dependent on level of illumination.

To summarize, the haploscopic experiments have shown that perceived hue, saturation and lightness of a test stimulus vary significantly with all three factors of adaptation: illuminant quality, illuminance, and luminance factor. The importance of illuminance and luminance factor is virtually coequal with that of correlated color temperature in determining changes in color appearance. But, unfortunately, they are the very factors that increase interocular disparities and thereby exacerbate the problems of haploscopic matching.

It is in large part to avoid these problems that some workers have recently turned to the experimental method known as 'direct scaling'. That term encompasses several techniques for deriving scales of perceptual extent, in terms of either intervals (distances or differences) or of magnitudes (ratios). In particular, some recent studies of chromatic adaptation have been carried out by the method of magnitude estimation where observers attempt to gauge the strengths of their color perceptions by assigning numbers to them. That method measures the change in color appearance of a stimulus as adaptation varies. This is the opposite of haploscopic measurement which specifies the change in stimulus required to maintain the same color appearance. The latter may be addressed by a different scaling technique called 'magnitude production' in which the observer adjusts a stimulus to match the magnitude of his perception to some numerical value.

One of the major appeals of these direct scaling methods is that observers may view test fields normally, without encumbrances, using both eyes in equal states of adaptation and with no recourse to memory of ulterior references. Since the same portions of the retinae are stimulated for each adaptation condition, the implied color matches are theoretically transitive. Of course, there are also problems associated with direct scaling. In the main, these are general problems of psychophysical scaling. They will be discussed in the following section. It is sufficient here to point out that if observers are merely consistent in their responses, the data may be treated in ways that result in the same kinds of information as that obtained from other methods of studying chromatic adaptation.

Two such experiments will be referred to here. Both involve surface color stimuli. The first was carried out in Japan under the over-all direction of Nayatani (Nayatani, Yamanaka and Sobagaki 1972; Sobagaki, Yamanaka, Takahama and Nayatani 1974; Sobagaki, Takahama, Yamanaka, Nishimoto and Nayatani 1975)[252,305,306]. The second was conducted in England (Pointer and Ensell)[270].

In the Sobagaki et al (1975)[306] experiment, stimuli consisted of 100 colored papers covering a range of chromaticities and luminance factors. Each paper was 5 by 5 cm and subtended 7° on a side. The stimuli were arrayed against a 74° by 53° surround of luminance factor 0.2. The surround appeared gray. Correlated color temperatures of the illuminants used for adaptation were 2,856 K (CIE Illuminant A), 4,200 K, 6,500 K, and 20,000 K. Each provided an illuminance of 1,000 lux at the sample plane. The entire display was contained in a viewing booth with gray-appearing surfaces of 0.43 luminance factor.

The 11 observers were familiarized with the scaling method and each performed a training experiment before undertaking the main work of the study. Relative scaling paradigms were used for hue, saturation and lightness. Hue was scaled as proportions of neighboring unitaries.

Saturation estimates for all samples were made in terms of "the percentage of maximum attainable saturation of a surface color with the same hue as that of the sample". When lightness was estimated, "the number 100 was assigned to the maximum lightness of surface colors". Observers were preadapted for 5 minutes before each of 9 sessions during which they scaled all three attributes of about 50 samples.

Results of this study were similar to those found in other studies of chromatic adaptation. No analysis was made of the influence of luminance factor. When a von Kries-type analysis was carried out, complex solutions were obtained for all 11 observers' data. However, what have been called 'adaptation coefficients' (MacAdam 1956)[231], corresponding to a diagonal matrix of the transformation matrix in Equation 4, were empirically determined by forcing consistency of achromatic samples at a luminance factor of 0.3. With these constraints, a linear approximation of the von Kries variety was obtained which led to predictions that were generally within about 3 units of CIE 1964 Colour Difference of the experimental data. When the transformation was applied to the Helson et al (1952)[138] data, predictions were about as good (or bad) as those based on the linear transformation derived by those authors for their own results. This finding is of interest primarily because it supports the premise that direct scaling data are at least no poorer than those of other methods.

The test stimuli in the Sobagaki et al experiment consisted of colored papers. Their chromaticities varied with illumination quality. This complication was avoided by Pointer and Ensell (1975)[270] who used 2^{o} stimuli produced by a self-luminous colorimeter field surrounded by a 20^{o} white-appearing area. The surround luminance was 110 $cd{\cdot}m^{-2}$ and all test luminances were 55 $cd{\cdot}m^{-2}$; an effective luminance factor of 0.5.

Hue was ~~scaled~~ according to the proportions of unitary hues. Lightness was scaled such that 0 represented 'black' and 100 corresponded to 'white'; also a relative scale. What was called 'saturation' was scaled on an absolute basis: "saturation was judged as the subjective difference between the colour and the grey that most closely resembled it, the same subjective scale being used for all hues, and no restrictions being placed on the numbers used. To assist the observers doing this, a grey scale, consisting of six steps, ranging from white to a very dark grey, was included in the field of view" (M.R. Pointer, private communication, April 28, 1975). Hence, 0 represented achromaticity and the scale had no clearly defined upper limit. The scale factor for each observer (later normalized according to range) depended solely on the number he chose to characterize saturation of the first stimulus presented to him.

The data were not intended to lend themselves to reduction as an adaptation transformation. What was done, instead, was to plot maps of isoattributes on CIE 1976 u',v' chromaticity diagrams for each of the two illuminant conditions studied (CIE Illuminants A and D_{65}). In this manner, no assumptions were made regarding the mechanism for chromatic adaptation. The data were simply set forth in a form that might be used in two ways: (1) to address practical problems empirically, and (2) to be used for evaluating proposed models of the chromatic adaptation process.

It may be seen, then, that a number of different experimental approaches may be used to study effects of chromatic adaptation. Some of these have yielded nominal data on color appearance; i.e., stimulus requirements for asymmetric color matches. Others have determined interval and magnitude estimates of changes in color appearance with adaptation. The direct scaling methods appear to be at least as good as the asymmetric matching methods. At best, direct scaling should be capable of providing considerably more information than that derived from an asymmetric color match, since direct scaling measures color appearances and not merely stimulus conditions for equality of color. In order to clarify these distinctions, it would be well to discuss briefly the theory and methodology of psychophysical scaling. The following paragraphs will do that.

Theory and methods of scaling.

'Psychophysics' may be taken as a general term referring to the measurement of sensation. Such measurements have quantitative utility if they can be expressed as numbers on a scale that is isomorphic with sensation. All quantitative scales are based on some criterion of invariance. In the case of sensory scales, some perceptual criterion of invariance forms the basis for the scale. Usually, one of three criteria is involved: (1) equality of sensations, (2) equality of threshold or suprathreshold differences in sensation, and (3) equality of ratios of sensations. They form measures that respectively may be called psychophysical equalities, differences, and ratios or magnitudes. In each case there is a quantitative isomorphic relation between stimulus (physical) and perceptual (loosely, 'psychological') parameters. The nature of those relations remains invariant over certain mathematical transforms: equalities are invariant over substitutions of equalities ($y = x$); differences are invariant over any linear transform ($y = ax + b$); ratios are invariant over any linear transform with zero intercept ($y = ax$). Such scales have been called 'nominal', 'interval', and 'ratio' respectively since those are the properties that remain invariant with permissible transforms (S.S. Stevens 1946)[314]. Other scale-types exist for other invariances (e.g., S.S. Stevens 1951; Torgerson 1958)[315,337].

Each of these three scale-types has a long history of use in psychophysics. In the early nineteenth century Fraunhofer (1815)[102] measured intensities of different spectral lights required to maintain equally bright sensations; a nominal scale. In 1760 Bouguer (1760)[33] measured intensity ratios between shadows and backgrounds required for threshold lightness differences; a threshold interval scale. Specifications for suprathreshold brightness differences have been traced back to Hipparchus in circa 150 B.C. (v. Jastrow 1887)[184] and in the nineteenth century Plateau (1872)[267] produced what is probably the first modern interval scale of lightness. Scales of sensory magnitude (ratio scales) have been produced by Krüger in 1743 (v. Marks 1974)[241] and affective response magnitude scales were suggested as early as 1728 by Cramer (v. Bernoulli 1738)[30]. Of these, the nominal and threshold interval have been used most frequently in sensory sciences.

The equality criterion is the basis for all conventional colorimetry and photometry. Such measurements represent unique specifications of the stimulus conditions for equality of appearance. But they yield no direct information about the nature of that appearance or how it varies with changes in stimulation.

The problem of how to measure variations in sensation resulting from changes in stimulation is one which has preoccupied many scientists. One such, who is celebrated as 'the father of psychophysics', was Gustav Theodor Fechner. We are told that while lying abed on the morning of October 22, 1850, the possibility occurred to him that each time a stimulus is doubled there is added a constant increment to the sensation (Fechner 1860/1966, pp.x-xvii)[98]. Fechner thus extended Weber's (1834)[355] concept of sensory threshold as proportional to stimulus magnitude to the domain of sensation. That is, Weber's expression:

$$\Delta\phi = c\phi \qquad (6)$$

becomes Fechner's:

$$\delta\psi = c\left[\frac{\delta\phi}{\phi_o}\right] \qquad (7)$$

Integration of this 'Fundamentalformel' yields Fechner's 'Massformel' or measurement formula:

$$\psi = k \log(\phi/\phi_o) \qquad (8)$$

where: ϕ = stimulus magnitude

ϕ_o = stimulus magnitude for absolute threshold

ψ = sensation magnitude

c,k = constants.

That derivation is a direct consequence of Fechner's conviction that sensation itself could not be measured: "a real measure of sensation would demand that we be able to call a given sensation twice, thrice, or in general so-and-so many times as intensive as another -

but who would claim that ...?" (Fechner 1860/1966, p.47)[98]. Therefore, he created a threshold unit of sensation, the 'just-noticeable-difference' (JND), and assuming it to be perceptually equal in size for all intensities of stimulation, he simply added up JND's to measure sensation indirectly. Accordingly, such psychophysical scales are said to provide indirect measures of sensation. Sometimes they are referred to as 'poikilitic measures' (S.S. Stevens 1975, p.10)[317] because the JND is taken to be a measure of variability or noise that sets limits to sensory resolving power. The idea of absolute or differential threshold variability as an additive index of perceptual extent has been widely accepted and also extended to suprathreshold intervals as 'the law of comparative judgment' (Thurstone 1927a,b)[331,332] and the related 'law of categorical judgment' (Torgerson 1954,1958)[336,337].

In order to implement his concept of threshold measurement, Fechner established - although he did not invent (v., Titchner 1905; Boring 1942)[333,32] - three basic methods of measurement: (1) limits, (2) constant stimuli, and (3) average error. The method of limits is an experimental procedure in which the stimulus is changed by successive serial increments until a point is reached where the observer's response changes. Usually the boundary between 'no change' and 'change' is approached from two opposite directions and the data are averaged. The method of constant stimuli involves presentation of stimuli to which the observer responds with either two categories (for absolute thresholds) or three categories of judgment (for differential thresholds); although two categories are sometimes used for differential thresholds as well. By treating each stimulus as a constant and recording the frequency with which it is assigned to the categories, one obtains a 'psychometric curve' on which the 50 per cent point is generally taken as indicating threshold. Finally, the method of average error provides a standard stimulus which the observer tries to match with an adjustable stimulus. The standard or average error of matching is taken to represent the threshold; although there is some logical basis for considering such measures to be subthreshold (e.g., Herbart 1824, p.3ff)[142]. In one way or another, then, all of these methods lead to expressions of stimulus magnitude corresponding to the absolute or differential threshold. Any scale, as such, must be built up by cumulative addition of stimulus values.

Scaling of suprathreshold differences or intervals has also been addressed by variations of these Fechnarian threshold methods. Matching of 'sense-distances' (Titchner 1905)[333], Wundt's 'method of mean gradations' (Wundt 1874,1907)[366,367], Müller's 'method of supraliminal differences' (Müller 1878)[249] and Delboeuf's 'sensible differences' (Delboeuf 1873)[72] have all drawn upon Fechner's methods of constant stimuli and average error to derive scales of difference. But generally, all of these workers have assumed that sensation itself is not directly measureable.

Not all workers have made that assumption. Plateau (1872)[267] used a 'method of bisection' which implies that an observer can recognize a sensation that is half as large as another by the simple expedient of matching two differences. Merkel (1888)[248] introduced what he called "die Methode der doppelten Reize", but it is clear that he meant 'doubling sensation' rather than stimuli. Fullerton and Cattell (1892)[107] used a method in which observers were instructed to produce stimuli that elicited both multiples and fractions of the sensation for a standard stimulus. All of these methods imply that sensations can be addressed directly. In fact, as early as 1874 Brentano (1874)[49] suggested an alternative to Fechner's fourteen-year-old law; an alternative which assumed that ratios of sensation are directly measureable.

Brentano assumed that Weber's law is also applicable to sensation. That is:

$$\Delta\psi = p\psi \qquad (9)$$

and by combining this with Weber's law for stimuli and integrating, we have that:

$$\left(\frac{\delta\psi}{\psi}\right) = \left(\frac{p}{c}\right)\left(\frac{\delta\phi}{\phi}\right) \tag{10}$$

which reduces to:

$$\psi = a\phi^{b} \tag{11}$$

where: ψ = sensation magnitude

ϕ = stimulus magnitude

p,c,a = constants

b = p/c .

Several other alternatives to Fechner's law have been proposed over the years (e.g., Helmholtz 1866; Broca 1894; Schjelderup 1918; Pütter 1918; Bénéze 1929; Zinner 1930; Guilford 1932; Woodworth 1938)[126,56,299,274,28,374,118,357] so that there may be seen to be two distinct classes of opinion regarding the matter of direct versus indirect approaches to measurement of suprathreshold sensation.

This dichotomy is one that has generated considerable argument over the years. In 1932 a committee was established by the British Association for the Advancement of Science to determine whether or not it is possible to make quantitative estimates of sensory events. The committee's final report (Ferguson 1940)[99] indicates an inability to reach consensus. A number of 'minority reports' were generated (e.g., Gage 1934; Campbell 1938)[108,64], some of them harshly polemic in nature.

There appears to be two principal matters of disagreement throughout such arguments: (1) what has been called 'the quantity objection' originally raised by James (1890)[175] against Fechner's original proposal (the objection that sensations are indivisible - do not have magnitudes - and therefore cannot possibly be multiples of other sensations), and (2) the definition of what constitutes a 'measurement'.

The first objection is basically a metaphysical one. Simply stated, the argument is that sensation is both private and indivisible. Because it is a private construct, we cannot 'get at it'; it cannot be abstracted and quantized in the same way that many simple physical phenomena can be abstracted and measured. The very term 'subjective' often carries perjorative connotations for many physical scientists. The notorious variability of subjective evaluations is mustered as an argument against such a schematic of measurement. But as Bridgman (1927)[52] has pointed out, all measurement involves uncertainty and variability. The penumbra of uncertainty that beclouds a measurement is not a useful index of either accuracy or utility; it only indicates something about the precision of measurement methods. Further, all measurement involves perception either explicitly or implicitly, for the constructs of measurement merely represent formal statements of things that are, in essence, perceptual observations. Campbell (1928)[63] uses measurement of length - what is often called a 'fundamental measurement' - to illustrate this point. Manipulations within the dimension length, it is said, do not require utilization of empirically determined relations with other dimensions. The operation of comparing yardsticks or adding lengths does not require reference to any ulterior dimension of physics. But is this really so? The very act of 'comparing' implies a judgment of contiguity of lines or parts of lines, and that is a perceptual process involving a subjective expression of sensation relations. Elaborate, modern techniques for length measurement do not change the fact that the concept of length and its measurement derives from just such homely observational empiricisms. Other more complex but equally compelling analogies may be provided for different physical dimensions; S.S. Stevens (1975, pp.289-291) gives one for temperature.

The point is simply that 'dimensions' are, after all, only logical constructs that we have chosen to call by that name in order to represent the schema of empirical observations. Many of those physical events and quantities share in common with the logical construct called 'sensation', the elusory character that is so often attributed to the subjective: we 'can't get at them'. Take, for example, the particles of nuclear physics. We can't get at them either. We may note by observation the presence of a crystal path in a cloud chamber and infer from that fact that an event has transpired. From the shape and length of the path we may even 'measure' the mass of the particle. Certainly such measurements are quantitative expressions of things just as private and inaccessible as sensations or perceptions. There seems to be no compelling reason why we should consider valid measurements of such things as force and magnetism and yet exclude sensation and perception from analysis by measurement.

The central question to the argument about direct versus indirect measurement of sensory events is then really one of how measurement is defined. And it is here that the concept of 'additivity' plays a paramount role; particularly for Newtonian physicists often encumbered by the restraints of Euclidean geometry. What is often overlooked is that the concepts of Euclid and Newton derived from models of observation. Those scientists merely created expressions for relations implied by the models. The expressions were useful and correct to the extent that they were in agreement with observation. Generally, the basic observations of natural science were simple by today's standards.

Stevens (S.S. Stevens 1975)[317] points out that the schema of measurement evolved from the operations of counting: "the central features of fundamental measurement stand out most clearly in the measurement of numerosity - the quantity of countable things like beans. All the principles of so-called additivity are reflected in the manipulations that we can perform on a pile of beans. We can determine equality of two piles. We can double the numerosity by combining two equal piles. We can show that the order in which the two piles add makes no difference; in fact, we can show that numerosity obeys all the axioms that govern in ordinary algebra. We are not surprised at the close correspondence between addition and the manipulation of beans, because it was just such manipulations that gave rise to elementary mathematics in the first place" (op.cit., p.44)[317]. Unfortunately, this relation has now been inverted in psychophysics. Helmholtz (1887)[127] decreed that the model shall dictate what kinds of operations may be called measurement; rather than modifying the model to reflect newly discovered empirical observations. Thus, additivity and its geometric consequence - distance - have become all-important in the argument about what constitutes a measurement.

The concept 'metric distance' requires that to be a valid distance measure, appropriate mathematical functions must have <u>all</u> of the following four properties:

1) the distance between any two points is never negative; $d(x,y) \geq 0$,
2) the distance between two identical points is always zero; $d(x,x) = 0$,
3) distance is symmetric; $d(x,y) = d(y,x)$,
4) the sum of the distances between two points by way of a third point is always equal to or greater than the direct distance between these two points; $d(x,y) + d(y,z) \geq d(x,z)$.

Details of the implications of these requirements are treated in a number of texts (e.g., Coombs, Dawes and Tversky 1970)[68]. Perhaps the most commonly used models that meet these requirements are those of the class of functions known as the 'power metric' (or the 'Minkowski r-metric'), defined as:

$$d(x,y) = \left[\sum_{i}^{n} \left| x_i - y_i \right|^{r} \right]^{1/r} \qquad (12)$$

where $r \geq 1$. The exponent, r, may be interpreted as a parameter of component weight. When $r = 1$, all components receive equal weight. That case is called the 'city block' model and total distance is the arithmetic sum of all component distances. As the exponent increases, components become increasingly differentially weighted according to their sizes. At the limiting case of $r = \infty$, (the 'dominance' model), only the largest component determines total distance. A special but common case is when $r = 2$; the 'Euclidean' model. Distances are invariant over coordinate translation for all values of r, but they are also invariant over rotation only for the case of $r = 2$.

Three basic properties of the power metric are: (1) interdimensional additivity, (2) intradimensional subtractivity, and (3) power. In the first instance the distance between two points is a function of the additive combination of the contributions of their components. In the second case, the distance between two points is a function of the absolute values of their component-wise differences. When these two properties are satisfied the model is one of additive differences. This is a metric assumption that perceptual distances among pairs may be properly represented as metric distances. However, in the instance of the third property - power - all component-wise differences are transformed by the same convex power function. This involves a nonmetric or dimensional assumption that points may simply be represented in a dimensionally organized space.

It is this third property, existing in isolation and involving power transforms according to any exponent, that Stevens argues should also be considered a valid measurement schema. He proposes a general, liberalized definition of measurement as the assignment of numbers to objects or events according to any consistent, non-random rule (S.S. Stevens 1946)[314]. Thus, any transform that preserves the invariance associated with any degree of isomorphism between two domains is properly a measurement. Certainly, some such measurements carry more information than others, but is this so uncommon a practical situation? Consider our use of maps. We choose different projections for different purposes. An azimuthal gnomic projection renders every global great circle a straight line. A Mercator projection yields loxodromes; lines that keep constant angles with parallels and meridians. Orthographic projections preserve neither areas nor angles but are satisfactory representations of our visual perception of a sphere. And so on. No map can be both area-preserving and conformal at the same time. The point is that we deliberately choose to minimize distortion of one property at a time according to our needs or interests. If we are interested in representations of distances as linear geodesics, we choose one kind of map. If we are interested in over-all impressions of area relations, we choose another kind of map. Why not the same logic for 'maps' of perceptual attributes? One kind of psychophysical measurement yields useful information about differences. Another kind of measurement provides an equally useful (but different) display of magnitude relations.

Thus, a psychophysical measurement may not necessarily result in a scale that has both distance and ratio properties at the same time. It is sufficient that a scale represent at least one invariance for a minimum of one class of isomorphism. To exclude direct measurement of sensation from the category of valid measurement merely because the resultant scales may not be linearly additive, is too parochial a view. It excludes many useful and even precise sets of information from the domain of quantitative consideration.

The dimensional organization associated with magnitude scaling of perceptions appears to obey rules for power transforms but does not have all four properties required for metric distance models. In particular, perceptual ratio scales frequently do not have symmetry of distances and the sum of distances between any two points and a third is not additive. In short, magnitude scales tend not to have distance properties. They do have ratio properties (i.e., logarithms of magnitudes are additive as metric 'distances'). Conversely, it is often found that difference scales of sensation do not agree with the ratios of magnitude scales. Some have argued that ratio scales are therefore incorrect; others have argued that difference scales are incorrect. But such arguments are sterile for we really have no way at present of determining correctness. Instead, we should choose whichever scale suits a particular need. The science of mathematics has progressed since the time of Fechner, so also should our utilization of the tools with which it provides us.

In practice there is some degree of cross-modal transitivity between interval scales and ratio scales. The correspondence is approximate, not exact. Magnitude scales and interval scales may both be expressed as some form of mathematical power function. However, for any one sense-modality, the exponent of the interval scale will generally be smaller than that for the magnitude scale (e.g., S.S. Stevens 1971; Marks 1974b) [316,242]. Interval exponents tend to be about one-half as large as magnitude exponents; implying a square-root relationship between the two scale-types. This relation seems to hold for those sensory continua called 'prothetic', which are characterized by intensive growth rather than substitutional change. Variability of prothetic continua tends to be proportional to magnitude whereas variability of the second kind of continua ('metathetic') tends to be constant with level.

There is also an approximate consistency between threshold data and magnitude scales of the prothetic variety. A number of experimenters have found that so-called poikilitic scales, derived from summations of JND's, are nearly linearly related to the logarithms of magnitudes (e.g., S.S. Stevens 1975; Indow 1961; Sellin and Wolfgang 1964)[317,168,303]. Whenever variability increases in proportion to level we might expect such a relationship if the JND does represent variability.

The theory of scaling has enjoyed an extensive vogue in recent years. So much has been written about theoretical relations in direct scaling that there sometimes seems to be a danger that the overlay of theoretical complexity may mask the underlying simplicity of direct scaling as an experimental technique. It is basically a simple process; so straightforward that even five-year-olds have been able to perform cross-modality scaling of loudness and brightness with results about as precise as those of adults (Bond and

Stevens 1969)[31]. It would be helpful, then, to review briefly the simple facts of magnitude scaling in order to see how the validity of magnitude scales can be assessed and maximized. This information is treated in a number of papers and has been summarized in books by S.S. Stevens (1975)[317] and Marks (1974a)[241].

Stevens identifies three kinds of measurement in psychophysics: (1) magnitude measures, (2) partition measures, and (3) poikilitic measures. The magnitude measure is a direct ratio of sensation or response elicited by a stimulus or pair of stimuli. It is expressed as a cross-modality match: "Magnitude measures become possible because people have a remarkable ability to match one thing against another. They can match numbers to apparent loudness or apparent loudness to numbers. They can match loudness to strength of a vibration on the fingertip, and vice versa. And they can match numbers or items from any other continuum to a nonsensory variable such as prestige of occupations" (S.S. Stevens 1975, pp.229-230)[317]. Most often, numerosity is used as the reference continuum. There are some workers who have questioned this practice; particularly the assumption that numerosity is linearly related to perception through the judgment process (e.g., Attneave 1962; Schneider and Lane 1963; Marks 1958)[5,300,240]. But since magnitude scales tend to form power functions, any nonlinearity of the number continuum which may also be represented as a power function merely changes the absolute values of all exponents by some constant factor. All relative exponent values remain the same. Therefore, in the absence of any better choice for a reference continuum, numerosity serves well as a standard.

It was noted above that the exponents of interval scales tend to be about one-half as large as those for ratio scales. Also, poikilitic scales are linear with log ratios. Thus, all three scale-types are nonlinearly related. Accordingly, significant differences may exist among results for different scales. Every experimenter must choose which scale to use in any given experiment. "There is no such thing as a perfect method of measuring anything. Magnitude estimation has its faults, but it has the great advantage of convenience... the observer brings one of the continua with him as the system of numbers that he has learned and practiced... (and)... can match numbers from that continuum to items on any other continuum with which he is confronted. The method calls merely for the presentation of a series of stimuli in irregular order, preferably a different order for each observer" (S.S. Stevens 1975, pp.29-30)[317]. The method of magnitude estimation then has much to commend it in the matter of simplicity.

As a result of considerable experimentation it has been found that unconstrained use of numbers, without either anchor or modulus, yields most unbiased results. A representative model of instructions to observers is:

> "You will be presented with a series of stimuli in irregular order. Your task is to tell how intense they seem by assigning numbers to them. Call the first stimulus any number that seems appropriate to you. Then assign successive numbers in such a way that they reflect your subjective impression. There is no limit to the range of numbers that you may use. You may use whole numbers, decimals, or fractions. Try to make each number match the intensity as you perceive it" (S.S. Stevens 1975, p.30)

It is often helpful, especially to inexperienced observers, to familiarize them with the process either by training or with a sample easy experiment such as apparent length of lines. Useful central tendency measures may be obtained from as few as 5 to 10 observers. Replications beyond 2 or 3 generally add no significant increase in information; in fact, replication may introduce systematic bias (S.S. Stevens 1975, pp.283-284)[317]. Since the individual observer's results form power functions (J.C. Stevens and Guirao 1964)[312] with variability approximately normally distributed as logarithms of response (J.C. Stevens 1957)[311], averaging to form a common scale can best be done by computing the geometric means of observations for each stimulus. This procedure has the additional advantage that "despite the different numbers that different observers may have assigned to the first stimulus, no normalizing is needed prior to averaging. The slope (exponent represented in double logarithmic coordinates) of the power function remains unaffected even though each observer has used a different unit or modulus for his subjective scale" (S.S. Stevens 1975, p.31)[317].

In the reverse procedure - magnitude production - the process is simply turned around. Logarithms of the stimulus intensities are averaged for each level of response numerosity.

It has often been noted that the exponents for magnitude production are somewhat higher than for magnitude estimation. That result arises from the tendency of an observer to shorten or constrict the range of whatever variable he is allowed to control. In estimation, his range of numbers tends to be constricted, while in production, his range of stimulus-adjustments is shortened. These tendencies are evidenced in the different exponents for the two methods of scaling. Scale constriction of this kind has long been known as the 'central tendency effect' (Hollingworth 1909)[146] but has recently been called the 'regression effect' in magnitude scaling (S.S. Stevens and Greenbaum 1966)[318]. It may be compensated by conducting two balanced experiments (estimation and production) and averaging the two exponents as an estimate of the 'true' value.

Observers may also tend to fit their range of responses to the range of available stimuli. When the stimulus range is small, the exponent tends to be higher than when the range is large (e.g., Poulton 1968; Teghtsoonian 1971,1973; Kappauf 1975)[271,325,199]. A reasonable approach to counteracting this tendency is to choose a stimulus range that is representative of the conditions that are of interest. Alternatively, one may conduct a balanced series of estimation and production experiments, plot the exponents as a function of range, and choose the cross-over value as representative of the 'true' exponent (S.S. Stevens and Poulton 1956;

S.S. Stevens 1971)[319,316].

The effect of an observer's tendency to use round numbers is avoided by allowing each subject to choose his own modulus. Such unconstrained use of numbers usually means that each person will choose a somewhat different number in response to the initial stimulus. When a geometric mean is computed, any round number tendencies will be averaged out of the data.

These, then, are the principal problems of direct magnitude scaling and known techniques for correcting them. The uncertainties of magnitude scaling are less numerous and less serious - and generally easier to correct - than those of other scaling techniques for suprathreshold responses (v. Thurstone 1927a,b; Pfanzagl 1959; Marks 1974a; S.S. Stevens 1975)[331,332,118,108,337,265,241,317]. Results of magnitude scaling have been shown many times to have internal consistency. The question of external consistency (i.e., validity) is a more difficult one to examine. Various techniques such as 'functional measurement' (Anderson 1971)[3] and 'conjoint measurement' (Luce and Tukey 1964)[226] have been used to approach the same experimental question from a number of different directions; results are then considered valid if all approaches converge on essentially the same answer. But, in general, the most practical approach to validation is that of comparing results with reliable prior work and known facts of perception and physiology; a common practice in all of psychophysics. Usually, a battery of evidence is more impressive than an isolated experimental result. Despite the considerable discussion and polemics on direct scaling of responses, careful comparisons of this kind provide no compelling evidence that magnitude scaling is any less valid a technique for mapping sensory attributes than any other psychophysical method.

The scales of magnitude measurement generally comprise power functions of the form:

$$\psi = \alpha \phi^{\beta} \qquad (13)$$

where: ψ = response magnitude

ϕ = stimulus magnitude

α = scale factor

β = compression (or expansion) factor .

The simple power function of Equation 13 does not always fit the raw data, however. Sometimes they describe a nonlinear function in double logarithmic coordinates (rather than the linear one represented by Equation 13). This is so particularly when the threshold is high or there is significant induction. A number of workers have proposed ways in which to 'correct' these nonlinearities; i.e., to produce a straight line in double logarithmic coordinates. Krantz (1972)[212] describes a correction based on a combination of Weber's law and Thurstone's law. But by far the most often used forms are what have been called the 'stimulus correction' (Ekman 1956)[86] :

$$\psi = \alpha[\phi - \phi_o]^{\beta} \qquad (14)$$

and the 'response correction' (Jameson and Hurvich 1964)[181] :

$$\psi = \alpha\phi^{\beta} - \psi_i \qquad (15)$$

where ϕ_o represents a threshold stimulus value and ψ_i is linked with response level and induction.

The stimulus correction form assumes that the stimulus parameter of importance is magnitude above threshold. Response correction implies that departures from a simple power function arise as a result of activity at neural response levels and, therefore, a response increment is more appropriate. When the stimulus correction is used, the exponent varies with adaptation and induction. However, when response correction is used, the exponent remains constant (usually at the level for the neutral state of the mechanism) and variation is reflected in values of the response increment. Each approach offers certain advantages but with any real set of data the two forms are not necessarily independent.

In order to illustrate this point, I have chosen a series of lightness scaling data as listed in Table III.

Table III

Scaled Lightness Data

100x Luminance Factor	Lightness								
	1	2	3	4	5	6	7	8	9
0.2	13	5	0	0	0	0	0	0	0
0.5	17	10	5	4	2	0	0	0	0
1.0	22	15	12	9	7	2	1	0	0
2.0	27	21	18	16	12	6	8	6	5
3.0	31	25	22	20	15	10	12	11	10
5.0	37	31	28	27	20	15	20	19	18
10.0	46	42	37	38	32	25	32	31	30
20.0	58	55	51	52	46	40	48	46	46
30.0	67	64	61	62	57	50	58	58	57
50.0	79	78	75	76	73	70	74	73	73
80.0	93	92	90	92	89	88	91	91	91
100.0	100	100	100	100	100	100	100	100	100

The data are from nine different experiments. Four relate to complex (i.e., pictorial) stimulus arrays and five involve simple fields. The complex field experiments were for the following conditions and according to the numerical column listings of Table III: (3) approximately 1^{o} elements of a pictorial image subtending 22^{o} by 14^{o} in an otherwise dark surround (Bartleson and Breneman 1967a)[20]; (5) approximately 1^{o} elements of a pictorial image subtending 22^{o} by 14^{o} with surround equal to 1/10th to 1/5th the luminance of the image element with maximum luminance (Bartleson and Breneman 1967b)[21]; (6) approximately 1^{o} elements of a pictorial image subtending 22^{o} by 14^{o} with surrounds of twice that subtense equal in luminance to the maximum image luminance displayed in an otherwise illuminated environment (Bartleson and Breneman 1967a)[20]; (8) approximately 0.5^{o} elements of an 8^{o} by 8^{o} pictorial image surrounded by a white-appearing 30^{o} by 30^{o} area having a luminance equal to that of the maximum for an image element (Bartleson, unpublished data). The simple field experimental conditions are: (1) 2^{o} stimulus presented for

2 seconds under dark adaptation conditions (Bartleson, unpublished data); (2) 5° stimulus seen in a 20° diameter surround of luminance equal to 1/100th of the minimum stimulus luminance (Bartleson, unpublished data); (4) CIE L* representation of Munsell Renotation Value (Wyszecki 1974)[370]; (7) 1° stimulus in a 15° by 15° surround of luminance equal to that of the maximum test luminance (present research); (9) 2° focal stimulus in a 40° by 50° surround of luminance equal to that of the maximum test luminance (Bartleson, unpublished data) 4 observers as for 1 and 2).

Thus, the experimental conditions involved a variety of induction situations and include both simple and complex stimulus arrays.

Table IV

Two Forms of Lightness Power Functions

Experimental Condition	(Eq 14) Response Corrected Function	(Eq. 15) Stimulus Corrected Function
1	$\psi = 21.55\phi^{\frac{1}{3}} - 0.0$	$\psi = 21.55(\phi-0.0)^{.333}$
2	$\psi = 23.50\phi^{\frac{1}{3}} - 9.0$	$\psi = 17.57(\phi-0.3)^{.378}$
3	$\psi = 24.66\phi^{\frac{1}{3}} -14.4$	$\psi = 14.29(\phi-0.4)^{.426}$
4	$\psi = 25.00\phi^{\frac{1}{3}} -16.0$	$\psi = 14.61(\phi-0.7)^{.422}$
5	$\psi = 25.66\phi^{\frac{1}{3}} -18.9$	$\psi = 10.31(\phi-0.6)^{.496}$
6	$\psi = 26.95\phi^{\frac{1}{3}} -25.0$	$\psi = 6.39(\phi-1.0)^{.608}$
7	$\psi = 27.23\phi^{\frac{1}{3}} -26.3$	$\psi = 10.28(\phi-1.4)^{.507}$
8	$\psi = 27.78\phi^{\frac{1}{3}} -28.9$	$\psi = 9.79(\phi-1.6)^{.518}$
9	$\psi = 28.00\phi^{\frac{1}{3}} -29.9$	$\psi = 8.72(\phi-1.6)^{.549}$

Each of the nine sets of data has been expressed as a psychophysical function in Table IV. Two functions are given for each column of Table III: a response corrected version and a stimulus corrected form. The coefficients of determination for all the functions ranged from 0.997 to 1.000.

Exponents of the response corrected functions are all 1/3; corresponding to the dark adaptation condition of experiment number 1. But the exponents of the stimulus corrected functions vary by a factor of nearly 2:1; from 0.333 to 0.608. That induction-dependence is also reflected in the response corrected functions as the variation in response increment values from 0.0 to 29.9.

When the exponents of the stimulus form are plotted against the response increments, as in Figure 1, a straight line may be drawn through the points as a good approximation of the relation. That relation implies two things of considerable importance. First, both exponent values and response increments are related in a rather simple manner. Second, both simple and complex field data are described by the same relation. This last point means that simple and complex field data differ only or primarily according to the amount of induction involved in the respective viewing situations. Thus, relations uncovered in experimental studies with simple fields will also be valid for complex fields up to a proportionality constant relating to amount of induction.

This interpretation - which is presented here for the first time - seems to explain a number of apparent discrepancies in the literature. For example, Hunt (1950)[153] found quite large changes in saturation for simple field arrays with and without light surrounds (somewhat smaller for 20° focal stimuli than for 1° stimuli). Pitt and Winter (1974)[266] found large changes in saturation between light and dark surround conditions for simple fields but smaller changes when the focal stimulus was part of a moderately complex array with and without light annuli. Breneman (1976)[48] reports very little change in saturation for elements of pictorial images when the entire picture is surrounded by light and dark environs. We may now see that the facts, originally determined for simple field conditions, are that saturation varies with intensity of induction. How much it changes depends upon the amount of induction provided by all elements within the field of view. Thus considered in terms of response increments associated with induction, the apparent contradiction of var-

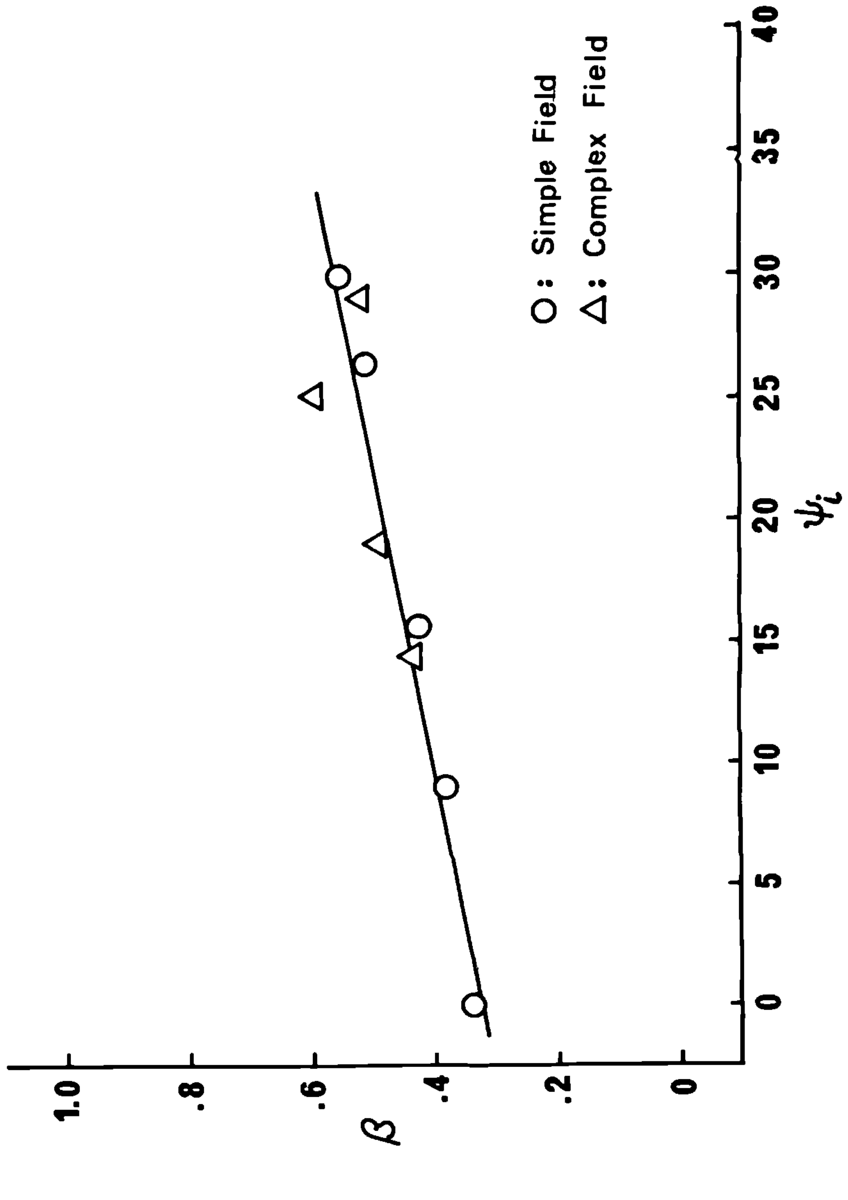

O : Simple Field
Δ : Complex Field
β
1.0
.8
.6
.4
.2
0
ψ_i
0
5
10
15
20
25
30
35
40

Figure 1

ious experimental findings is reduced to a cohesive set of unified results.

The response-corrected, psychophysical function may then be seen to be useful for evaluating induction and other response-related factors. On the other hand, the stimulus-corrected function provides a direct indication of the gain or compression factors for sensory response under different conditions. Both kinds of expression are useful for different purposes.

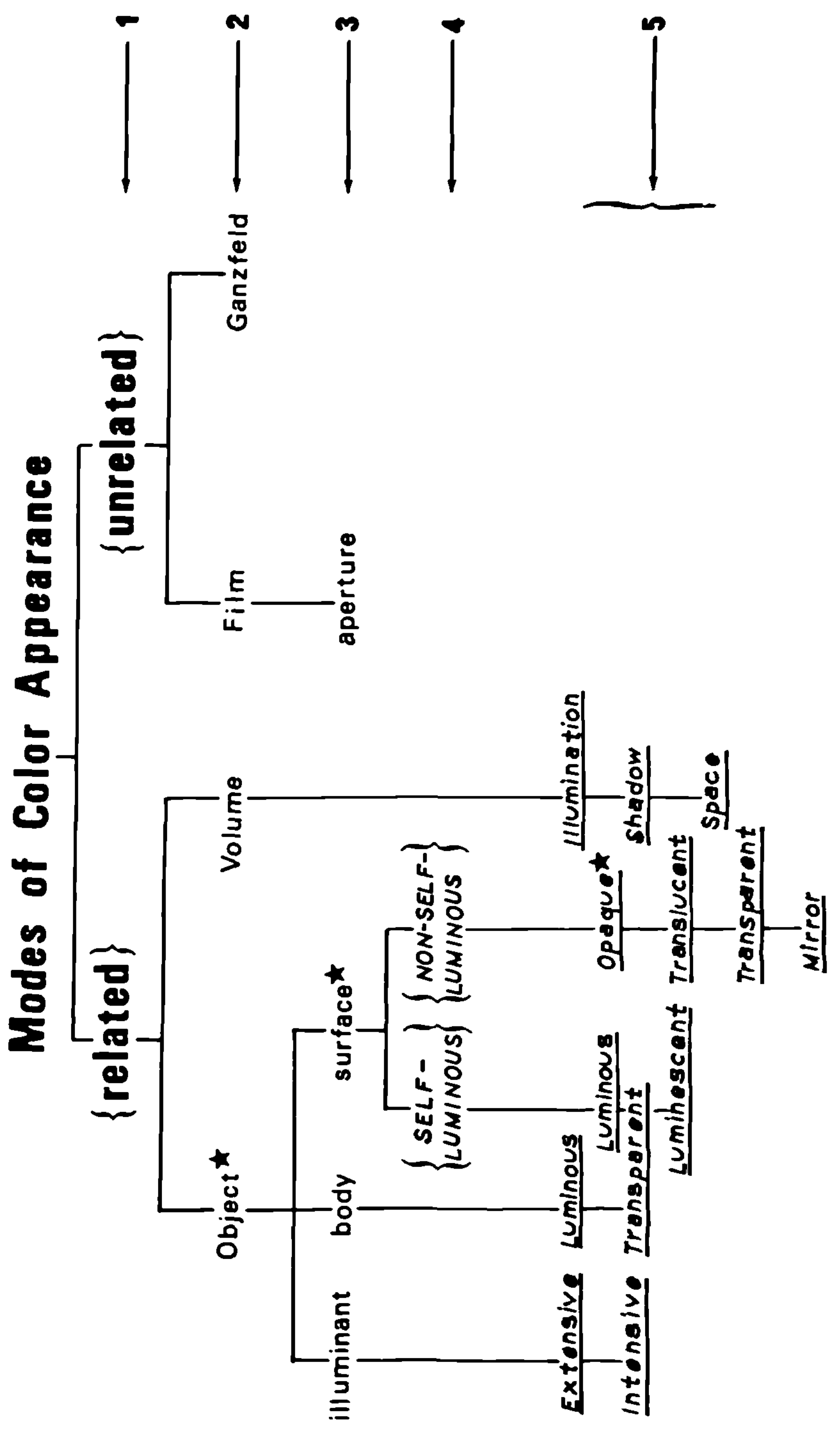
Either form of psychophysical function may usefully be applied to extended examinations of data relations. That is, a number of inferences may be drawn beyond the psychophysical function itself as a representation of experimental findings from direct scaling. Direct scaling is an extension of classical measurement techniques of psychophysics. It can provide more information than matching and threshold approaches to measurement because it measures magnitudes of sensation directly. Direct scaling can also yield the same kinds of information that is obtained with classical, indirect methods. The indirect methods evaluate sensory response in terms of variations in corresponding stimuli; a kind of 'sensory physics' (v. Marks 1974a, p.4)[241]. Typical examples include isosensation loci expressed in physical units such as luminances required for equal brightness or purity required for least perceptible saturation increments, and so on. These too may be obtained from magnitude scaling data; for example, by computing or reading from curves the luminances that produce equal brightness magnitudes, or purities that yield constant saturation ratios, etc. But in addition, magnitude scales tell us something about the growth of sensation with stimulation. We can also determine psychosensorial relations (i.e., interrelations among sensory variables without regard to stimuli) from such growth curves. In short, magnitude scaling opens up the possibility of collecting more information than has been possible with older psychophysical methods. As a bonus, the method of direct scaling is convenient and straightforward, economical of experimental labor, and easy for observers to carry out. It seems only sensible, then, that such methods should be used to map the attributes of color perception. If those attributes can be defined in ways that are understandable to observers, magnitude scaling offers a potentially powerful approach to the study of chromatic adaptation. It is appropriate, then, that we examine the matter of attributes of color and define those that may be independent indices of the perceived variations in color with changes in chromatic adaptation.

Dimensions, attributes, and modes of color appearance.

Color may be experienced in a number of different ways according to a variety of frames of reference. Katz (1911,1930)[201,202] systematically developed a descriptive structure for distinguishing among the various ways in which we perceive colors. He called that phenomenological complex 'modes of color appearance'. Katz listed 11 modes and others have since proposed from 3 to 10 or more categories (e.g., Troland 1929/1930; Evans 1948; Newhall 1953)[338,89,253].

Basically, any description of the modes of color appearance involves distinctions among separable components of a color percept according to structural relations of the percept. One such set of distinctions is illustrated in Figure 2. The most general distinction is that between related and unrelated colors. Most color perceptions are of related colors, and of those we are primarily interested in object colors. Opaque surface colors - a subsidiary division of related object colors - comprise the bulk of all common color perceptions.

It should be emphasized that these structural relations are among percepts and not stimuli. Regardless of the stimulus configurations that underly them, it is the relations among appearances that are important in determining how we see colors. When those relations are unequivocal, we perceive color in only one mode at any one instant (Burnham, Hanes and Bartleson 1963)[62]. Equivocal situations may cause a color appearance to fluctuate between two modes of appearance, but the color will not exist in transitional states between



Modes of Color Appearance
{related}
{unrelated}
Object★
Volume
Film
Ganzfeld
aperture
illuminant
body
surface★
{SELF-LUMINOUS}
{NON-SELF-LUMINOUS}
Extensive
Intensive
Luminous
Transparent
Luminous
Transparent
Lumihescent
Opaque★
Translucent
Transparent
Mirror
Illumination
Shadow
Space
1
2
3
4
5

Figure 2

modes (Martin 1922; Gibson, Purdy and Lawrence 1955; Avant 1965; Beck 1972, pp.22-25)[244,111,7,26]. Some unequivocal, complex stimulus configurations may elicit perceptions that permit an observer to shift attention from one mode to another; for example, as in distinguishing among color, illumination, and spatial location of a surface color (Kardos 1928; Koffka 1935; Wallach 1948; Beck 1959)[200,207,347,25], but again, the shifts are distinct and abrupt rather than gradual. They are the result of changes in attitude or attention.

There is an exclusive-inclusive relationship between modes of appearance and attributes of color. "Modes of appearance and the attributive and functional properties of color are interrelated. Certain attributes such as hue, saturation and brightness are present in all modes of appearance. An investigation of these attributes in the film mode has been useful for investigating the sensory processes of color perception. It is, however, an abstraction to consider the perception of color apart from modes of appearance... Many attributes occur only in connection with certain modes of appearance" (Beck 1972, p.24)[26]. The attribute of lightness, for example, is perceived with opaque, translucent and transparent surfaces. But we do not speak of the lightness of an illuminant or a film color simply because we do not see lightness in those modes of appearance. Many attributes of color may exist, but they do not all occur at the same time or under the same conditions. Within the total set of all color experience, there are a number of sub-sets, only some of which are congruent. The structural relations of visual experience determine functional inclusion or exclusion of the various attributes of color.

Bartleson and Breneman (1967a,b,; Bartleson 1972)[20,21,18] have devised a perceptual schema that recognizes the fact that different modes of appearance permit perception of different color attributes. In addition, they have proposed that color perceptions may be absolute, relative, and object-oriented. "The term 'absolute' is used to refer to the most abstract, generic, or introspective attitude... the 'relative' orientation... utilizes arbitrary reference points which serve as comparisons for evaluating ratios of absolute responses... when these references coincide with perceptually meaningful conditions of the object-world about us, we have the most naive, least introspective, and for our everyday experiences, most important orientation: the 'object' orientation...." (Bartleson 1972, pp.43-44)[18]. Put most simply, the object orientation is the attitude we adopt when we want to know the nature of the stimulus; the absolute orientation relates to our evaluation of a sensory event in terms of all possible sensation; and the relative attitude allows us to evaluate our sensations in terms of what we see at the moment.

Table V has been prepared to illustrate these relationships among modes of appearance and attributes of color perception. A general distinction between absolute and relative attributes may be made in terms of the number of perceptual anchors or references involved (Bartleson 1976)[19]. Absolute attributes are described on scales with only one anchor; usually with a modulus of 0 representing the lower limit of sensation for the attribute in question. Relative attributes are characterized by scales with two anchors; defining both a lower and an upper limit. One kind of relative scale (R_1 in Table V) has an arbitrary upper-scale anchor. A second kind (R_2) has an upper-scale anchor that coincides with some perceptually unique reference such as white or a unitary hue. Some of these relative scales have been given special names. 'Lightness' is one such name used to distinguish brightness-relative-to-white from brightness itself. Similarly, we have saturation and chroma as forms of colorfulness. But there are no special names for some of the other relative forms.

This plurality of color attributes has sometimes been confused with the dimensionality of color. In the case of brightness alone, there are proposals for bidimensionality going back at least as far as Hering (Hering 1874; Judd 1960,1961; Evans 1964; Lie 1969;

Heggelund 1974)[143,188,189,92,225,123], and there have been proposals for three dimensions (Katz 1935)[203] and as many as five dimensions (Evans 1959b)[91].

Table V

Color Attributes and Modes of Appearance

Mode of Appearance	Brightness				Hue				Colorfulness				No. of Attributes
	A	R_1	R_2	O	A	R_1	R_2	O	A	R_1	R_2	O	
UNRELATED													
Ganzfeld	*				*				*				3
Film	*				*				*				3
RELATED													
Illumntn	*	*		*	*			*	*	*		*	8
Shadow	*	*	*	*	*	*	*	*	*	*	*	*	12
Space	*	*	*		*	*	*		*	*	*		9
Opaque	*	*	*	*	*	*	*	*	*	*	*	*	12
Translcnt	*	*	*	*	*	*	*	*	*	*	*	*	12
Transpnt	*	*	*	*	*	*	*	*	*	*	*	*	12
Mirror	*	*	*	*	*	*	*	*	*	*	*	*	12
Luminous	*	*	*	*	*	*	*	*	*	*	*	*	12
Luminscnt	*	*	*	*	*	*	*	*	*	*	*	*	12
Trpnt Body	*	*	*	*	*	*	*	*	*	*	*	*	12
Lmns Body	*	*	*	*	*	*	*	*	*	*	*	*	12
Ext Illnt	*	*	*	*	*	*	*	*	*	*	*	*	12
Int Illnt	*	*	*		*	*	*		*	*	*		9

KEY:

* : occurs
A : absolute
R_1,R_2: relative
O : object

Most recently, Evans (1959a,1974; Evans and Swenholt 1967,1968,1969)[90,93-96] has argued that there are at least five dimensions for color appearance of surface colors; two for brightness, two for saturation or colorfulness, and one for hue. He refers to these as 'independent dimensions'. Unfortunately, there are two common definitions of what is meant by 'dimension' applied to color perceptions; a classical definition by Titchner and a newer one by Stevens.

Titchner's (1910)[334] definition of dimension corresponds to the usual mathematical usage of that term; i.e., as equivalent to degrees of freedom. He proposed that to be a dimension, a perceptual attribute must be capable of independent variation while all other dimensions are held constant. According to this definition, lightness (a relative form of brightness) cannot be a dimension. Lightness is not independent in the sense that it cannot be varied without also changing brightness. Brightness, on the other hand, can be altered (for example, merely by increasing illuminance) without an accompanying change in lightness. Since brightness may be varied without changing either hue or saturation (or any of their relative derivatives), we may say that brightness is an independent dimension according to Titchner's definition. As it happens, no relative attribute qualifies as an independent dimension under Titchner's proposal. Thus, when dimension is equivalent to degrees of freedom, we find no evidence that supports a dimensionality greater than three for color. All other attributes listed in Table V may be deduced from relations among three dimensions for two or more stimuli. This is not to say that three numbers or descriptors are sufficient for completely describing all color perceptions. What is implied is that three dimensions are necessary and sufficient for each stimulus in the field of view. Given that information, interrelations and relative values may be determined for all the stimuli. Three numbers are sufficient only in the unusual case where there is a single stimulus in the field of view (e.g., aperture or film colors and the Ganzfeld). In that simple case, the three attributes required turn out to be the three basic (Titchnerian) dimensions of color: hue, saturation and brightness.

Some people have argued that Titchner's definition of dimension is too strict. They prefer the more liberal proposal of S.S. Stevens (1934)[313]. His is the logical complement to Titchner's definition. According to Stevens, an attribute must be capable of being held constant while all other dimensions are varied if it is to qualify as a dimension. This criterion yields phenomenologically distinct loci in color space but not necessarily the property of independence. Using Stevens' definition, both brightness and lightness are dimensions; assuming complete freedom to manipulate all stimuli in the field of view. It is on such a definition that Evans bases his claim for five dimensions of color (v. Evans and Swenholt 1969, p.631)[96].

Admittedly, the attributes that qualify as dimensions under Stevens' definition are of considerable practical interest. But they may each be determined from the dimensions of Titchner as well. It does not seem necessary to abandon the mathematical power of independent dimensions merely to serve the purpose of generating a plurality of related and interrelated specifications that can be deduced from independent dimensions of the stimuli in the field of view. Basically, the argument for use of a more liberal definition of dimension is a carry-over from unrelated, simple field, conditions - a desire to characterize only the single stimulus of interest in a field of view. Although it is held that such characterization provides more information, it turns out in fact to contain <u>less</u> information than three-dimensional specifications of every stimulus in the field of view. The relative attributes can be derived from three-dimensional specifications of all stimuli, but those dimensions cannot be computed for all stimuli from the relative attributes.

Relationships of perceptual extents can be just as useful concepts as attributes along underlying independent dimensions as they would be if they formed a confluence of dependent dimensions. Accordingly, I have chosen here to use Titchner's definition of independence and dimension: a color attribute is a dimension only if it is capable of being varied while all other attributes are held constant. Dimension here is then equivalent to degrees of freedom.

With that stipulation, 'color' will be defined as an aspect of visual perception, apart from temporal, spatial and structural aspects of that percept, by which a sensing human observer may distinguish appearances that are conjointly specifiable on independent dimensions comprising an integrated percept.

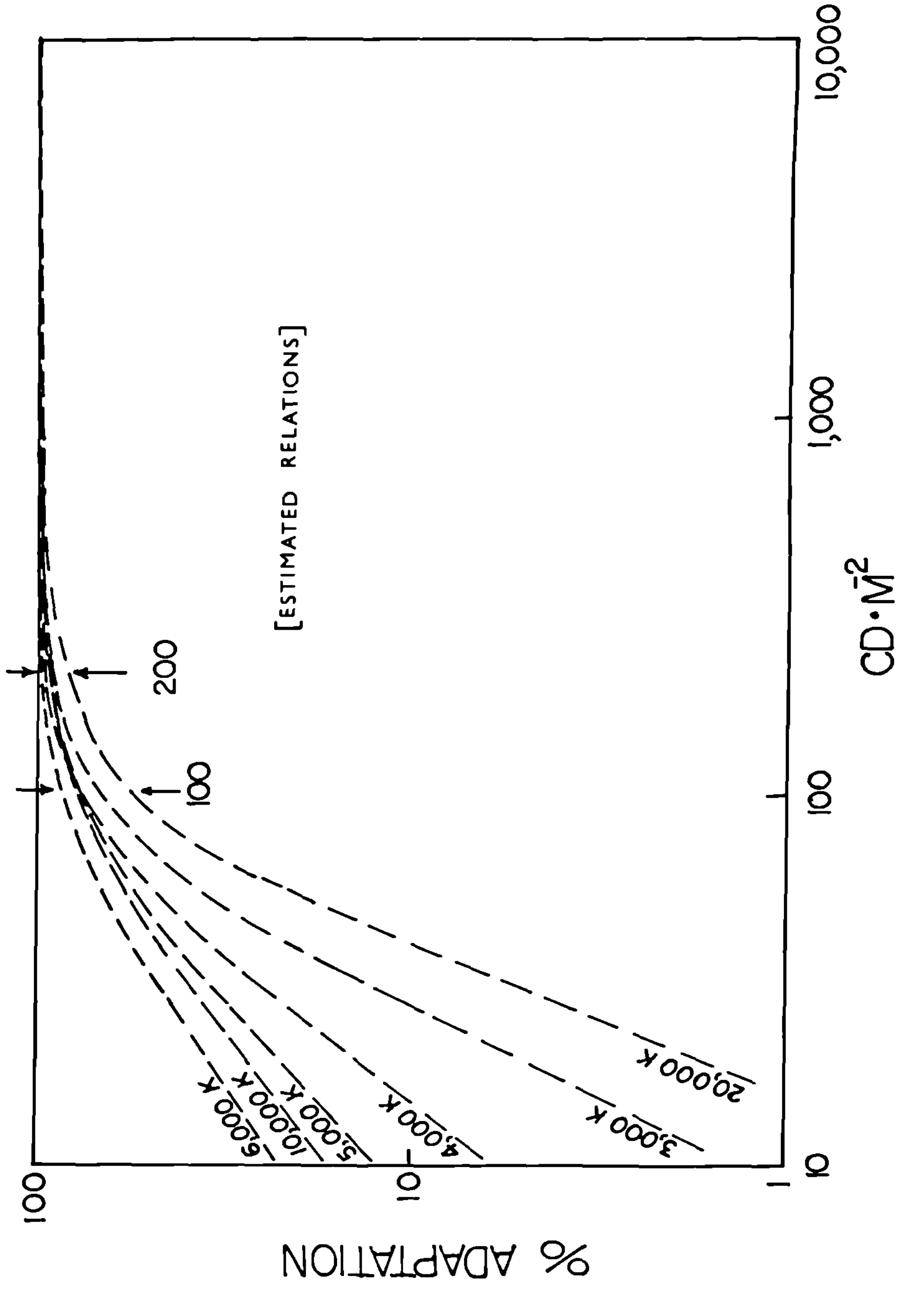
Attributes that relate to stimulus structure (e.g., clarity, texture, gloss, etc.), however much they may affect color appearance, are not part of color by this definition. Attributes such as lightness, gray content, and so on are not considered dimensions. Thus, there must be three descriptors for each stimulus in the field of view, corresponding to the three basic dimensions. In the case of a simple field with only one focal stimulus in a constant surround, three descriptors are adequate to specify either the absolute or the relative color quality of the focal stimulus (but not both) if the surround remains constant in color appearance. In that case, considerable freedom attends the choice of attributes to be specified, provided only that they each relate to a separate, independent dimension.

This research will treat changes in three attributes of color appearances of samples that appear in the surface color mode of appearance. The exact meaning of this statement is explicit in the definitions and explanatory matter set forth above.

Surface color appearance.

There are a variety of factors that determine the obviousness of different attributes in the surface mode of appearance. Principal among these are (a) illumination level and uniformity, (b) 'whiteness' of a reference surround, (c) induction, (d) texture, (e) contour, (f) pattern, and (g) attitude of observers. It is important that each of these factors be controlled to prevent unwanted variables from influencing results.

In general, illumination should be uniform over the total stimulus area. In addition, there is a minimum level of illumination that may be used if surrounds are to appear 'white'; i.e., achromatic with zero gray content. Hurvich and Jameson (1951a,b)[161,162] have studied the stimulus requirements for perception of white. They find a number of factors to be critical. Primary among them is illuminance. A certain minimum illuminance is required for the perception of white depending upon size, exposure time, chromaticity, and previous adaptation history. In general, the correlated color temperature of the illumination that requires least illuminance is somewhat higher than the correlated



% ADAPTATION
100
10
1
CD·M^{-2}
10
100
1,000
10,000
[ESTIMATED RELATIONS]
100
200
6,000 K
10,000 K
5,000 K
4,000 K
3,000 K
20,000 K

Figure 3

color temperature of the adapting illuminant. The luminances of surface colors required for threshold white perception increase sharply at both lower and higher color temperatures. Below the threshold, a highly reflecting, spectrally nonselective sample or surround will appear either bluish or yellowish; depending on whether the color temperature is higher or lower than that of the most efficient white-producing light for the viewing condition in question. Similar results have been found for viewing conditions that differ from those used by Hurvich and Jameson (Bartleson and Witzel 1967)[23]. Also, Hunt and Winter (1975)[160] determined the chromaticity coordinates for stimuli that appeared white after five minutes adaptation to one of two levels of illumination by sources of different color temperatures. They found that neither 35 nor 70 $cd{\cdot}m^{-2}$ was high enough to permit observers to adapt fully to the light; i.e., highly reflecting, spectrally nonselective material did not appear white. Instead, the chromaticities of stimuli that did appear white tended to be intermediate between those of the adapting sources and a coordinate position near Illuminant E (the 'equal-energy source'). The higher luminances produced white-points that were closer to the adapting light chromaticity.

All of these experimental results indicate that a surround luminance must be above some minimum level if an observer is to perceive it as a white surface. In order to provide a general estimate of this minimum, I have taken data from all three experiments and combined them to illustrate the approximate extent of adaptation as a function of surround luminance. Figure 3 shows the general trends for several correlated color temperatures of illumination. The surround subtense assumed here is of the order of 10° to 30°. That figure shows that illumination in the range of 5,000 K to 10,000 K is generally more efficient for evoking white sensations than higher or lower color temperatures. Over the range of quality included in Figure 3, it appears that a minimum luminance of between 100 and 200 $cd{\cdot}m^{-2}$ is required for a near-100 per cent reflectance material of this subtense to appear white. As a general guideline, then, surround luminances should not be less than 200 $cd \cdot m^{-2}$ if they are to appear white.

Luminance factor of a sample, with respect to its surround, influences color appearance. The amount of induction depends upon a number of factors. In general, the test field appearance depends on the ratio of test-to-surround stimulation (e.g., Diamond 1953,1955,1962a,b; Heinemann 1955,1972)[74-77,124,125]. When the inducing field does not completely surround the test field, the effects are much smaller. When the test field is textured, the effect is also smaller (Berman and Liebowitz 1965)[29]. Size of the test field and surround are also important (e.g., Helson 1963,1964; Helson and Rohles 1959)[134,135,141]. Contour, sharpness of demarcation, and other factors affecting obviousness of separation between test field and surround, influence apparent contrast (e.g., O'Brien 1958; Evans 1959b; MacLeod 1940; Beck 1972)[259,91,237,26] and may even influence whether a sample appears in the surface mode of appearance (Koffka and Harrower 1931; Fry 1931)[208,103] or the film mode (MacLeod 1947; Kanizsa 1969)[238,198].

These are but some of the stimulus factors that influence color appearances of surface color samples. There are other cognitive factors that also influence color. It is easy to see that surface color perception is a complex process involving many phenomenological parameters. Care should be used in the design of experiments intended to measure the influence of chromatic adaptation to ensure that the results reflect only those variations in color arising from adaptation and not unwanted variation attributable to ulterior factors. In addition to constraining luminances and luminance factors, the experimenter should avoid texture and make certain that test stimuli are well defined with sharp borders and as nearly as possible are completely homogeneous. It is probably good practice to have all fields be of the same simple, abstract shape if size is not a parameter under study. In short, one should take care to recognize the complexities of surface color perceptions and to minimize the influence of all factors that are extraneous to chromatic adaptation.

Obviously, the generality of results will be limited for any one set of viewing conditions. They apply to the same or nearly the same conditions of stimulation. But if care is taken, there can be a minimum of confounding factors. In addition, the relationships, if not the absolute values, can be assumed to have broad implications; even when extended to complex stimulus arrays.

Since there is little data that describe changes in color appearance of surface colors throughout a total color solid, the research undertaken here should add new information to our existing store of knowledge about chromatic adaptation. The psychophysical magnitude functions and maps of color space derived from them should provide a novel insight into the ways in which color appearance depends upon chromatic adaptation factors.

II. Design of the Experiment

The primary objective of this research is to provide data that subsequently may be used to derive a method of predicting color appearances of surface color stimuli with changes in chromatic adaptation. This objective has been addressed by scaling the magnitudes of selected attributes of color with variations in three stimulus factors (viz., color temperature, illuminance and luminance factor) in order to derive dimensional maps that describe the influence of those factors on the color appearances elicited by invariant surface color stimuli. A number of factors influenced the experimental design. The most important of these were:

a. chromatic adaptation stimulus conditions and ranges to be studied,

b. attributes of color appearance to be studied,

c. number and chromaticity gamut of samples to be included in the study,

d. number, availability and comittments of observers,

e. methods of scaling to be used.

Each of these considerations will be discussed in the following paragraphs.

Adaptation conditions.

Most studies of chromatic adaptation aimed at generation of data for practical application have been concerned with adaptive shifts between some daylight illuminant and some incandescent quality illuminant. The overriding reason for this is simply that the range of correlated color temperature of practical interest in commerce and industry is that from about 2,500 K to 7,000 K. This seems a sensible basis for choosing CIE Illuminants A and D_{65} as limiting conditions for such a study of chromatic adaptation. A good case may be made for including other highly selective illuminants in a physiological study of the mechanism for chromatic adaptation, but this research is not physiological in thrust. Therefore, the limiting color temperatures for study here are those represented by CIE Illuminants A and D_{65}; viz., 2,856 K and 6,504 K.

Since prior work indicates that adaptive shifts are not necessarily linear with color temperature or its derivative characterizations, a third illuminant was also selected. That illuminant is one which closely approximates the chromaticity of CIE Illuminant D_{44}. It provides a color quality roughly midway between the two extremes on a scale of reciprocal megakelvins. These three illuminants cover the range of correlated color temperature of general interest. Being three in number, they permit determination of simple nonlinear relations.

Colorimetric specifications and relative spectral power distributions of these adapting illuminants as reflected from the surround are given in Appendix A.

There are other stimulus factors that need to be considered as well. Viewing conditions is one of these. Surface colors may appear in either simple or complex fields. We have seen that while the absolute degree of color shift depends upon induction, and hence on field-complexity, relative shifts may show the same trends for both simple and complex fields. Since simple field configurations are both easier to specify and to control, they have been chosen for this study. Surface color stimuli in illuminated, white-appearing surrounds were selected as the mode to be studied.

Since the main interest of the study centers on chromatic shifts attributable to differences in stimulation of cone receptors, a stimulus array that would tend to maximize cone activity and minimize rod participation was selected. The focal or sample stimuli were chosen to be circular with a diameter of 1° visual subtense. This covers the entire foveola and probably only includes the rod-free portion of the fovea. The sample stimulus was surrounded by a square, white-appearing area of 15.2° on a side; equivalent on average to a circular area of about 17.2° diameter. This represents a retinal circular area of about 5,000 micrometers, which is roughly 90 per cent of the perifovea and contains perhaps 80 per cent of all cones (v. Wyszecki and Stiles 1967, Tables 2.1 and 2.2, pp.205-206)[373]. Thus, with central fixation, both sample and surround should evoke primarily cone activity.

The surround should establish and control the observer's adaptation. This is usually accomplished by requiring him to view the surround for a period of time long enough to allow sensitivity to stabilize. The amount of time required for this depends upon a number of factors including size of surround, its chromaticity, and its luminance. Previous experiments with surround sizes and chromaticities similar to those used here have allowed from about 5 minutes (at 200 to 1,000 $cd{\cdot}m^{-2}$) up to 45 minutes (for dark adaptation). Computations based on earlier experimental data (Wright 1946; Hunt 1950)[364,153] indicated that about 10 minutes should suffice for the levels used in the present work. That figure was multiplied by a factor of two in selecting a 20 minute preadaptation period for use here to ensure that all observers would be stably adapted and, hence, perceive the surround as white. As a check on the extent of adaptation, observers were required to scale the appearance of the surround at various times throughout each experimental session to ascertain that it did, in fact, appear to be white.

It was decided that tachistoscopic presentation would be used to minimize the influence of samples on the observers' adaptation. The work of Burnham et al (1952,1957)[60,61] provides a guide to choice of duty cycles that permit adaptation to be virtually completely controlled by the surround. Preliminary experimentation indicated that a continuously alternating cycle of 2 seconds sample presentation followed by 8 seconds in which an extension of the surround was substituted for the sample, allowed all visible trace of sample-induced after-images to disappear before the sample reappeared when both sample and surround luminances were 1,000 $cd{\cdot}m^{-2}$. Since all samples in the experiment had luminance factors less than unity, it is assumed that there were no intrusions of after-images in the experiment and that adaptation was controlled by the white-appearing surround. The 2 second sample presentation is about an order of magnitude higher than the Broca-Sulzer response latency period, so it is assumed that physiologically stable responses ensued for all test stimuli.

A number of adaptation studies have used only one level of illuminance. However, it has been shown that illuminance significantly influences color appearance; particularly saturation. Accordingly, chromatic adaptation data intended for practical use should include illuminance as a parameter of study. As we have seen, the minimum luminance required to evoke a white perception for a high reflectance, spectrally nonselective area of approximately the subtense chosen for the surround in this work is of the order of 200 $cd\cdot m^{-2}$. That luminance was then chosen for minimum here. The upper limit may be quite high depending upon the practical situation to be simulated. A paper illuminated by direct sunlight may have a luminance of about 75,000 $cd\cdot m^{-2}$. The same paper in an incandescent-lighted living room may have a luminance of only 50 to 200 $cd\cdot m^{-2}$. Outdoors on a dull day its luminance may be around 1,000 $cd\cdot m^{-2}$ (v. Hunt 1975, p.587)[158]. In practice, the upper limit for experimental apparatus is often proscribed by equipment limitations. However, one should expect to achieve a level at least equivalent to that of dull daylight (i.e., 1,000 $cd\cdot m^{-2}$) if results are to be generally applicable to real situations represented by the range of color temperatures under consideration. That is, in fact, the upper limit for surround luminance that was used in this work. Three levels of effective illuminance were chosen for study: corresponding to surround luminances of 200, 500, and 1,000 $cd\cdot m^{-2}$. The middle level was chosen simply to provide an intermediate condition that would permit determination of simple nonlinear variations arising from level effects.

Finally, we have seen that luminance factor influences color appearance. Although a number of experimenters have pooled data over luminance factor, it is also a parameter that should be studied if the results are to have practical utility. For this reason, three levels of luminance factor were chosen for the test samples. These were 0.43, 0.20, and 0.07. They represent Munsell Values of 7, 5, and 3 respectively. The Value 5 level was chosen as the one of greatest interest. Its position on a lightness scale placed it about half-way between white and black. In addition, its luminance factor (0.20) is roughly representative of a random, average sampling of naturally occurring surface color stimuli (Jones and Condit 1941)[185]. Both higher and lower Values were also included. Value 7 was chosen because it permits a reasonably large gamut of chromaticities with samples that appear in the surface mode for both extreme color temperature illuminants. Value 3 was selected because of its essentially symmetric lightness relation to the others and because experience has shown that sensory evaluations of samples much darker than Value 3 become increasingly difficult.

The number of combinations for stimulus conditions considered is fairly large: 3 color temperatures, 3 illuminances, and 3 luminance factors making 27 conditions in all. When multiplied by the number of stimuli, attributes to be scaled, and replications, a representative number of judgments for each observer would be in the neighborhood of 6,000. Assuming about one-half minute for each judgment this would mean 50 hours of labor for each observer without considering time for preadaptation. Translated into elapsed time, such an experiment would require up to 8 months to carry out; a formidable undertaking for most observers.

Accordingly, the total number of observations was reduced for most observers in a way that should still permit extraction of all the desired information. The following considerations were made in abbreviating the experiment:

1) It was assumed that the major relation of interest would be that among the three color temperatures for a representative luminance factor and illuminance. All

observers would scale all samples at Value 5 for an illuminance yielding 1,000 $cd \cdot m^{-2}$ surround luminance with each of the three color temperature illuminants.

2) Illuminance was considered to be of secondary importance to color temperature, but since the effect might be different for different color temperatures, at least two illuminant qualities should be used. Therefore, all observers should scale Value 5 samples for two illuminants at each of three illuminances corresponding to surround luminances of 200, 500, and 1,000 $cd \cdot m^{-2}$.

3) Luminance factor was considered to be tertiary in importance and could be satisfactorily evaluated by having a smaller number of observers determine adjustment factors by which results from a representative luminance factor condition could be modified. This technique has been effective with the Munsell spacing (e.g., Newhall, Nickerson and Judd 1943)[255]. Since the effects may depend on color temperature, at least two illuminant qualities should be used. Accordingly, three observers would scale all stimuli at Values 3, 5, and 7 for both D_{65} and A illuminants, with 1,000 $cd.m^{-2}$ surround.

By following this scheme, the total hours of observation could be reduced by a factor of about three and the experiment should still yield nearly the same reliability of information.

Attributes of color appearance studied.

Table V (on page 67) lists as many as 12 attributes for surface colors. Obviously, not all of them are equally important or informative. Those relating singularly to object-identification are of little interest in studying chromatic adaptation. Others are merely relative forms and therefore represent some redundancy of information. In this reasearch, spatial relationships among stimuli remain constant; all stimuli are of the same size and shape and all appear in a constant-size surround that always evokes a white perception. Accordingly, an adequate specification of color appearance may be obtained for these conditions with as few as three color attributes, provided that they are separately related to the three basic dimensions of hue, saturation and brightness.

Hue proportions is an appropriate choice for one of the three attributes since the objective of this research can be satisfied by producing dimensional maps of color appearance for each of the adaptation conditions studied. Any shifts in hue appearance will be reflected in the hue proportions.

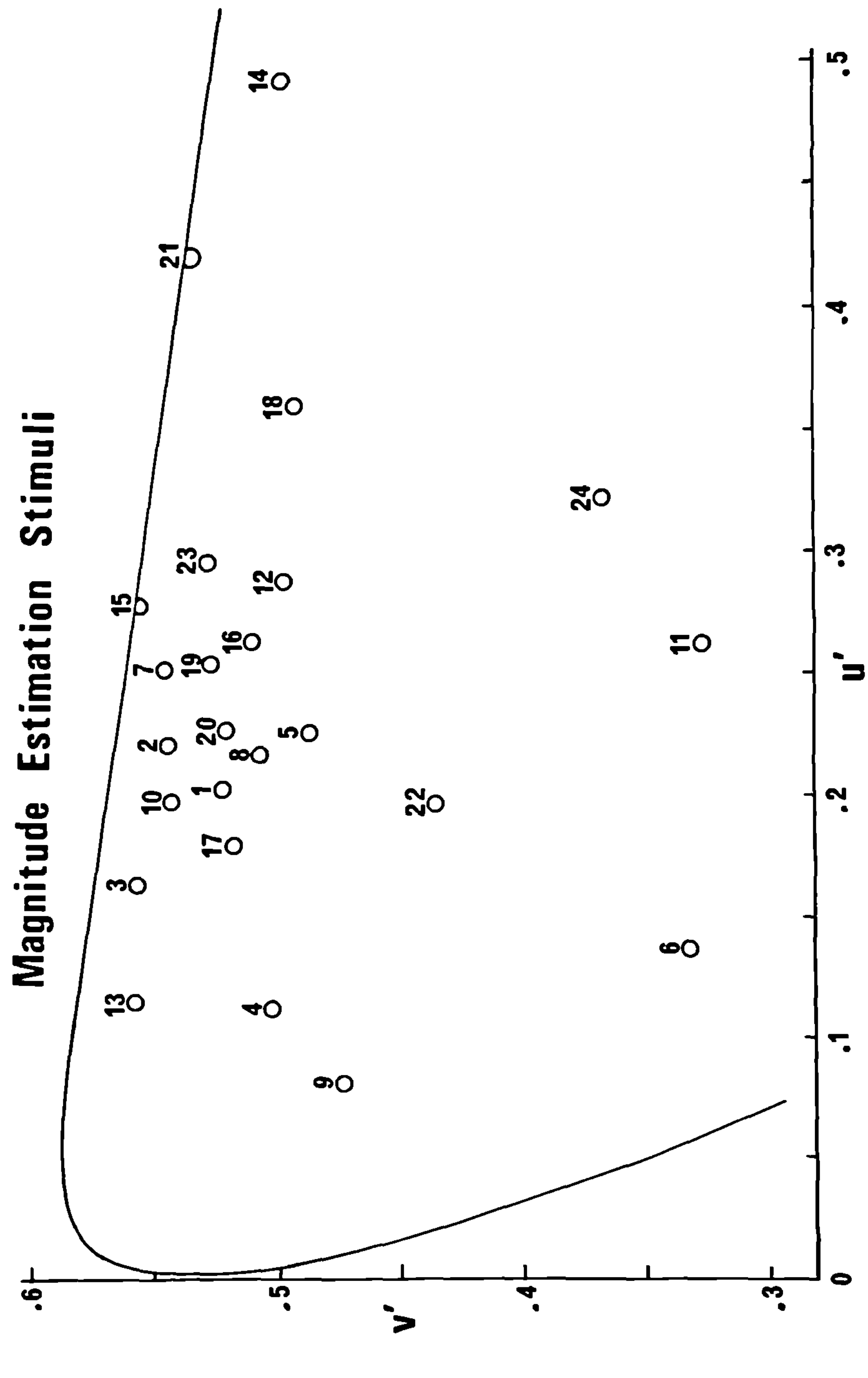
In the case of saturation, however, relative attributes might normalize, and therefore mask, variations that depend upon luminance factor and illuminance. Accordingly, absolute saturation should be scaled.

Brightness, rather than lightness, might be a logical choice for the third attribute for the same reason that absolute saturation is preferred. However, many of the appearance relations of interest can be as easily determined from lightness. Since lightness is easier to scale than brightness, it might be favored. But in either case, there is a wealth of information about the attribute available from other experiments. For that reason, it should be sufficient to explore such relations in a separate, limited experiment requiring less time and effort than if either were to be scaled for all stimuli under all conditions. This is the alternative that was selected; primarily to reduce the over-all size of the experiment.

The primary responses required of observers were then hue proportions and absolute saturations. Both brightness and lightness were studied separately by a smaller number of observers; although all observers did make some assessments of lightness.

<u>Samples</u>.

Various numbers of samples have been used in studies of chromatic adaptation; as few as 12 (Burnham et al)[61] to as many as 100 (Sobagaki et al)[306]. A primary concern is that the samples represent a reasonable gamut of chromaticities corresponding to naturally occurring collections of surface color stimuli (v. Padgham and Saunders 1975, Fig.11-4, p.177)[262]. That should also


Magnitude Estimation Stimuli
u'
v'
0
.1
.2
.3
.4
.5
.6
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24

igure 4

be the goal of this experiment.

It seems reasonable to select a sample size intermediate between those noted above for each luminance factor level to be investigated. Accordingly, an initial selection of 46 samples for each of the 3 luminance factors was made. Their chromaticity gamut represented a nearly uniform sampling of chromaticities corresponding to the distribution of typical colorants found in everyday situations. The gamut was centered on Illuminant E; the so-called 'equal energy' neutral point. Illuminant E was chosen as centroid because it was considered desirable to use stimuli that are independent of surround illumination. This was accomplished by using a self-luminous test field. Unlike reflecting stimuli, such independent stimuli retain the same chromaticities regardless of illumination quality used for adaptation. There is, then, one less degree of freedom for accumulation of errors in colorimetric specification of the test stimuli.

Preliminary experimentation indicated that some of the 46 stimuli did not serve to increase information significantly. Their chromaticities were too similar. Therefore, the number of samples was reduced. The final selection included 24 independent samples for each level of luminance factor; effectively 72 stimuli in all. The chromaticity coordinates with respect to Illuminant E are listed in Appendix B for each of the samples. They are displayed graphically in Figure 4.

Observers.

The committment in time and effort required of observers was a significant factor in determining how many people could, realistically, be expected to participate in the experiments. If his data were to be useful, each observer must carry out the entire program assigned to him. Accordingly, an aim of between 5 and 10 observers was set. Of 8 observers selected from the initial screening process, a total of 7 completed the entire experiment. They each performed a minimum of 12 to a maximum of 50 hours observation.

The screening and selection process involved a battery of color vision and performance tests. The classifications according to these tests of the 7 observers and their 'average observer' are set forth in Table VI.

Each observer is identified in the first column of that table by an alphabetical index to protect his or her privacy.

The second column assigns an 'experience' index to each observer. Experience was arbitrarily defined as extent of previous participation in scaling experiments. An index of 0 indicates that the observer had never before performed scaling of any kind. An index of 1 refers to observers who have taken part in between 1 and 10 scaling experiments of any kind. An index of 2 identifies observers who have participated in (usually many) more than 10 scaling experiments. Of the 7 observers, two had no previous scaling experience, two had extensive experience, and the average observer had moderate experience.

Column three of Table VI lists the observers' ages. They ranged from 20 years to 53 years at the time the experiment was conducted. The average observer's age was 34.9 years. Figure 5a shows their cumulative per cent frequency distribution of ages. A normal ogive, based on the biblical 'three score and ten' is included for reference. The cumulative distribution of observers' ages is a reasonable simulation of the normal distribution. The average observer's age (34.9) is virtually coincident with the normal 50 per cent point (35.0).

As shown in column four, 5 observers were male and 2 were female; making the average observer a biased hybrid of about 2.4:1 parts male.

Color vision of the observers was tested with a Nagel anomaloscope. Each observer performed three matches and three determinations of acceptable upper and lower match limits with each eye. In every case, the interocular differences were equal to or less than the acceptable deviations about an observer's mean matchpoint. The average of match and range mid-point, to-

Table VI.

Observer Characteristics

Obs.	Exp.	Age	Sex	Anom. Quot.	CAT Score	CAT Time	%e Hue	%e Sat.
A	2	47	M	1.020 (±.005)	87	1.18	1.48	5.46
B	0	48	F	1.032 (±.004)	67	0.65	2.09	24.33
C	1	23	M	0.983 (±.037)	69	2.00	2.43	12.47
D	2	53	M	0.958 (±.041)	64	2.15	1.62	10.78
E	0	20	M	1.057 (±.025)	58	0.95	2.63	25.34
F	1	29	M	1.001 (±.006)	82	0.75	0.88	13.21
G	1	24	F	1.002 (±.007)	64	1.15	1.42	13.68
Avg	1.0	34.9	-	1.008	70.1	1.26	3.34	12.76

KEY:

Experience
- 0 = none
- 1 = moderate
- 2 = high

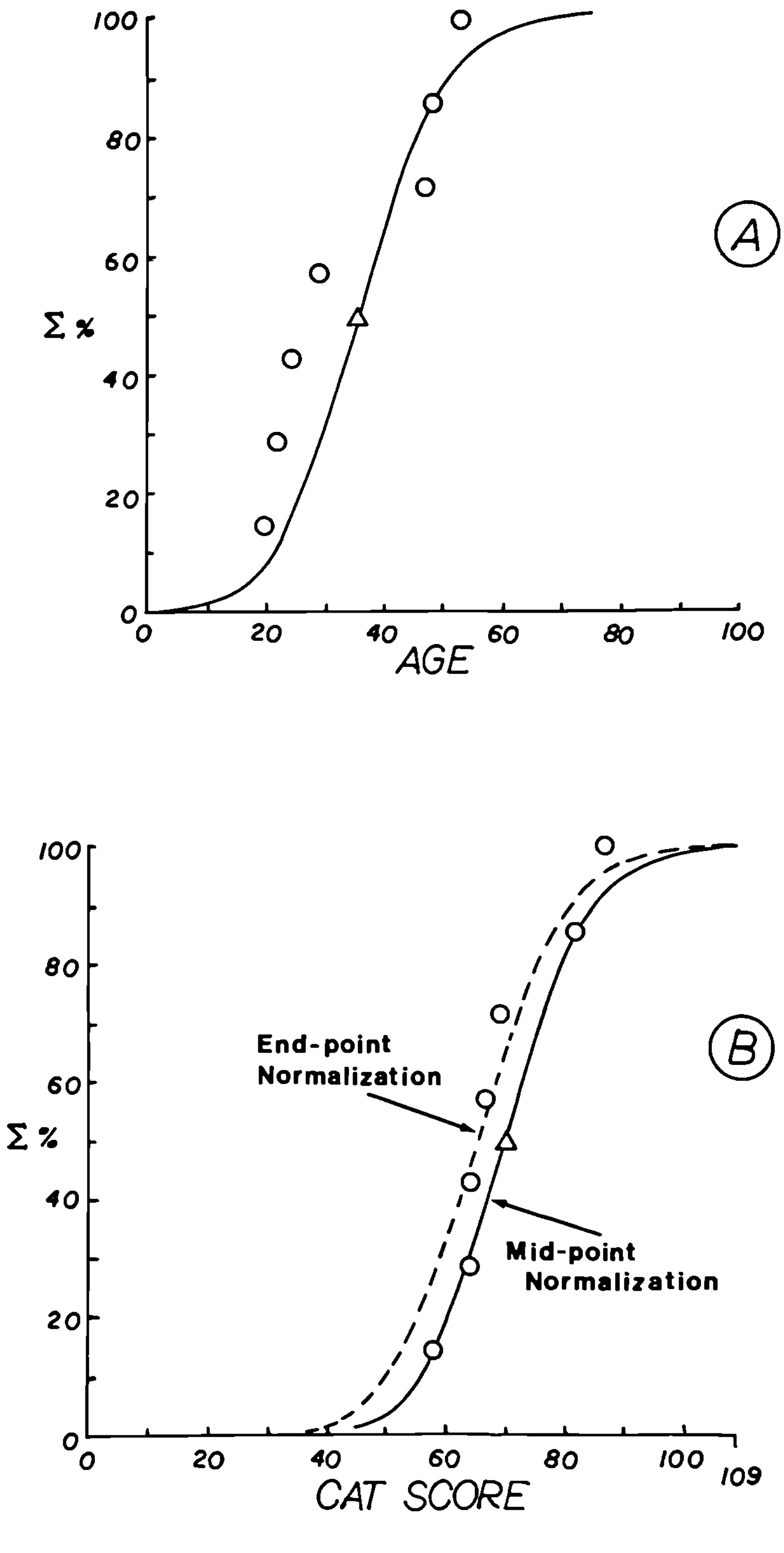
Anomalous Quotient
- 1.00 = normal mean
- 3.16 = deutan mode
- 0.35 = protan mode

CAT Score
- 0-48 = "poor"
- 49-65 = "fair"
- 66-74 = "average"
- 75-83 = "good"
- 84-109 = "excellent"

CAT Average Time
approximate average time for 40 samples is 45 minutes= 1.125 minutes/match.

%e = mean probable error in per cent of level.
$e = 0.674\sigma$

gether with the mean positive and negative acceptable deviations, is shown for each observer in the fifth column. The numbers listed are anomalous quotients; i.e., the proportion of anomaloscope reading to mean normal trichromat reading. A value of 1.00 corresponds to the normal mean. Deuteranopic means are about three



A
Σ %
AGE
B
Σ %
End-point
Normalization
Mid-point
Normalization
CAT SCORE

Figure 5

times higher and protanopic means are about one-third the normal mean on this scale. The data show that all observers had normal trichromatic vision. The average observer's mean of 1.008 is very close to a 'perfect' score. In addition, the anomalous quotients of all observers were nearly the same - within a range of 7.4 per cent - indicating that there were not large differences in color matching characteristics among the 7 observers.

Each observer carried out a full ISCC-Color Aptitude Test (essentially a test of saturation discrimination, despite implications of the test's name). ISCC-CAT scores may range from 0 to 109. The range has been divided into five descriptive categories intended to provide general characterizations of an observer's ability to discriminate small color differences. Column six of Table VI indicates that the 7 observers' ISCC-CAT scores ranged from 58 ("fair") to 87 ("excellent"). The average observer's score was 70.1 ("average"). Figure 5b shows the cumulative distribution of score frequency for the observers. Two normal ogives are included for comparison since the ISCC-CAT score range is not symmetric with the central category. The solid ogive is based on normalization about the CAT score mid-point; i.e., the center of the "average" category. The dashed function is based on normalization of the scale end-points. Whichever ogive is used for comparison, it may be seen that the distribution of scores for the 7 observers was reasonably normal. In addition, the average observer's score (70.1) is virtually coincident with the 50 per cent point on the mid-point normalized ogive (a value of 70.0).

In addition to the CAT scores, the time required for completing the test was recorded. A representative time for carrying out all 40 matches is 45 minutes, or an average of 1.125 minutes for each match. The actual average times for each observer are listed in column seven. They range from 0.65 to 2.15 minutes/match; or roughly from half to twice the representative rate.

Table VI also provides two additional columns of data tabulating the mean probable errors for hue and saturation scaling for each of the observers. These data were extracted from the final results but they are included in Table VI because they help to define reliability characteristics of the observers. The mean probable error is an inverse indication of precision in scaling hue and saturation; the smaller the number, the higher the precision. Mean probable error is equal to 0.674 times standard deviation as averaged over all observational sessions. It is expressed here in per cent of magnitude. Values for the average observer are not simply averages of the individual mean probable errors, but are computed from the pooled standard deviations of all observers over all sessions. Some correlation may be noted between the mean probable error for saturation and the experience index in column two.

Finally, data from the observers' lightness scalings were analyzed according to the four-part classification used by Bartleson and Breneman (1973)[22] for evaluating reliability of observers in magnitude scaling work. All 7 observers here were of the Type I class; the class found to be most reliable according to the consistency criteria used by Bartleson and Breneman.

Thus, all the data set forth in Table VI indicate that the observers constituted a representative normal group in all respects considered except for sex distribution. It is interesting to note that, for the most part, the correlations among the different measures of observer characteristics appears to be low, suggesting that they represent independent factors.

Scaling methods.

The method of magnitude scaling was selected for use in this work. That choice was made for a number of reasons. The principal considerations were as follows:

1) Direct scaling would avoid problems associated with either memory or haplscopic matching - extended training periods and distorted memory traces on the one hand, and binocular interactions on the other.

2) Magnitude scaling would allow observers to use normal, binocular viewing of all stimuli without inter-

position of encumbrances in the field of view and with assurance that the observer's entire visual mechanism was uniformly adapted to the conditions under test. In short, direct scaling would allow normal viewing conditions to be used.

3) Magnitude estimation permits scaling of the change in appearance of a fixed stimulus resulting from variations in adaptation as opposed to the change in stimulus required to evoke the same color appearance. Such adaptational metamers may be derived from magnitude estimation data but the change in appearance cannot be determined from haploscopic data.

4) Magnitude estimation preserves absolute differences of attributes induced by variations in illuminance and luminance factor.

5) An aim of the work is to produce dimensional maps of color attributes and magnitude scaling is well suited to that purpose.

6) Magnitude scaling is most economical of observer's time and effort, and since the experiment was to be extensive, the magnitude approach seemed a sensible choice.

A training or introductory period was considered desirable since both experienced and inexperienced observers would participate in the work. A series of training sessions would serve a number of useful purposes. It would permit establishment of a common metalanguage for judgment responses. All observers could see (actually experience) the kinds of changes in color appearance that would be encountered in the main experiment and they could be taught to describe those appearances with a uniform and parsimonious set of words. Training sessions would also permit gathering preliminary data that, in addition, could serve two different purposes. Data on lightness scaling could be used for screening and to test the manner in which observers tended to respond with judgments. Also, by using the method of magnitude production during part of the training period, data could be generated which would be helpful in assessing internal consistency of the scales derived from magnitude estimates in the main experiments.

That way, the same questions could be approached from two different methods of measurement to determine whether or not the observers yielded consistent results. Finally, a training period would allow the observers to see variations in several attributes of color and learn to distinguish those which were to be the subject of investigation. The training period was considered an important phase of the research in order to ensure uniformity of response structure and certainty of understanding in the judgment process.

For these reasons, each observer began his work with one or two sessions, amounting to one-and-a-half to three hours depending upon his previous scaling experience. In these sessions he learned to carry out both magnitude production and magnitude estimation. Primary emphasis was on production during the training period. In all sessions, the observer was allowed to adapt for 20 minutes to a uniform area (consisting of the surround plus occluded central stimulus area) at 1,000 $cd \cdot m^{-2}$ with D_{65} chromaticity illumination. During a session, all samples were presented at a luminance factor of 0.20.

Lightness was addressed first. The procedure was as follows. Sample luminance had been set at essentially zero luminance. The observer was given a control which changed only the luminance of the sample. Sample chromaticity was very close to that of the surround. The observer was then instructed that:

"You will probably see a very dark circle in the center of the field."

(After affirmative response):

"Please turn the control knob in a clockwise direction with your left hand and tell me what you see."

(Observers typically responded with descriptions such as 'brighter', 'lighter', or 'turns gray')

"Continue to turn the knob slowly in the same direction and see if you can make the circle as bright as the surround."

(After a match is achieved):

"Now we may say that the surround and the sample have the same brightness. Another way of describing their relationship would be to say that they have equal lightnesses. Now I want to tell you how we will distinguish between these two ideas of lightness and brightness. We will use the word brightness in reference to how bright or dark something appears in terms of all the brightnesses that you can remember ever having seen. Think of seeing a piece of white paper outdoors with sun shining directly on it. Is the white area in front of you as bright as that? (Observer responds) Now think of the same white paper outdoors on a moonlit night. Is the white area in front of you as dark as that? (Observer responds) So you see that you can distinguish how bright something appears in terms of your past experience. That is how we will use the word brightness to describe what you see. On the other hand, we will use the word lightness in a relative sense. Right now the sample and surround are also equal in lightness. We can assign an arbitrary number to that lightness. For example, we could call it 100. So both sample and surround have a lightness of 100. Now turn the knob in a counter-clockwise direction. Are they still equal? How would you describe the difference? (Observer responds) The sample now appears darker; it is no longer white but is a light gray. We can say that it contains some gray. We will use the word lightness only when the sample appears to contain some gray. If it contains gray, then it no longer appears white - correct? If the white surround has a lightness of 100, then the sample must now have a lightness less than 100 - agreed? Turn the knob some more in the counter-clockwise direction. What happens to the appearance of the sample? (Observer responds) Now it is dark gray - its lightness is even less than before. We could say that it has less whiteness in it than before. Turn the knob some more. Now you see an even darker sample; it is a darker gray or, alternatively, it has still less whiteness. In either case, its lightness has been further reduced. If you can reduce the lightness far enough (NB: some observers could and some couldn't do this) you will see that it contains no trace of whiteness - no lightness - at all; that is, it appears perfectly black. We could call that condition a lightness of 0. We will define lightness as applying to all those colors between black and white. They all contain some amount of gray. We can assign a number to the lightness of any of those colors. Since black doesn't contain any whitness or grayness, we can say its lightness is zero. At the other end of the scale we have the white surround. It appears only white. It has no trace of gray. We will call its lightness 100. Lightness runs between 0 and 100 from black to white. With that in mind, can you turn the knob until you are satisfied that the sample has a lightness of 50? (Observer responds) Now adjust it to a lightness of 75. (Observer responds) Now make it 100." etcetera.

"So you see that you can assign numbers to how light the sample appears. Those numbers tell me how you see its lightness. They are your best estimate of what you see. There are no correct or incorrect answers; your best estimates are all that count."

"Now please adjust the sample so that it is brighter than the surround. (Observer responds) We might be tempted to say that its lightness is now greater than 100. But remember that I said we will define lightness in a relative sense and only for those colors that contain some gray. Does the sample now appear to contain any gray? (Observer responds) Then we will not talk about its lightness but, rather, its brightness. Now in terms of all the other brightnesses that you have ever seen, what number do you feel best represents the brightness of the sample that you now see?"

(Observer responds with a number N)

"Now can you turn the knob so that the brightness of the sample is $\frac{1}{2}$N ?"

(Observer responds with luminance adjustment)

"Does it now appear to contain any gray?"

(After affirmative response)

"Then what is its lightness?"

(Observer responds with number X)

"So the brightness and the lightness are not the same. Certainly $\frac{1}{2}$N does not equal X. You can see, then, that the same sample can be described in two ways. The brightness ($\frac{1}{2}$N) is relative to all the brightnesses you have ever experienced. The lightness (X) is relative to the brightness of the surround that you now see. In that sense, lightness can be thought of as a kind of relative brightness. So we can talk about both absolute brightness and relative brightness. When we talk about relative brightness for samples that contain gray, we use the word lightness. But the two ideas are different and the numbers that represent brightness and lightness are not necessarily the same. Do you understand the distinction I am making between lightness and brightness? Do you agree that it is a reasonable distinction?"

(After observer responds, experimenter asks him to adjust the stimulus to produce several lightnesses in turn. Then the experimenter asks him for several brightnesses. Next, the experimenter introduces a reddish filter into the stimulus beam)

"Now how would you describe the appearance of the sample?"

(Observer responds)

"Can you turn the knob so that the brightness of the sample matches that of the white surround?"

(Observer responds by performing a match)

"Does the sample contain any gray? (Observer responds negatively) Is it brighter than the surround? (Observer responds negatively) Then we could say that its lightness would be 100 - agreed? Now see if you can turn the knob to make its lightness 50. (Observer responds) Does it now contain any gray? (Affirmative response) So you see we can talk about lightness and observe that colors may contain gray even if they are reddish-appearing rather than neutral gray. In other words, lightness is one attribute of what we see when we look at colors and we can abstract that attribute from all other aspects or attributes of color appearance in order to describe it alone. We can even assign numbers to it to describe the intensity of our lightness perceptions in the presence of other, different, aspects of color."

(Experimenter then guides the observer through the same steps as with achromatic stimuli, and subsequently substitutes green-, yellow-, and blue-appearing filters in the stimulus beam, repeating the entire procedure for each condition).

This procedure is set forth in some detail because it serves as a logical model for introducing other attributes of color. In addition, the logical and linguistic structure developed in the training phase is an important key to understanding the exact nature of the results of the experiments to follow.

During the exercise with lightness and brightness, the observer has learned to use the two words in a consistent way to describe two attributes of color. He has learned to distinguish between absolute and relative attributes. He has also learned to abstract one attribute from among several in order to attend only to it. Finally, he has learned to assign numbers to intensities of attributes in a consistent manner or, alternatively, to adjust a stimulus to match a number representing intensity of attribute. During the process he has gained first-hand perceptual experience within the context of the viewing conditions to be used in the main experiment.

In learning the attribute structure and metalanguage for hue, each observer began by producing a unitary yellow hue. He was provided with the same knob for stimulus adjustment. This time, however, it controlled dominant wavelength rather than luminance. The range of adjustment permitted hues to be produced with continuous variation between a generally yellowish-appearing red to a distinctly yellowish-green. The observer was first allowed to see how hue could vary systematically. The attribute hue was identified and named according to that variation. He was then required to make an adjustment that produced "a yellow hue with no perceptible trace of any other hue". This hue was named "unitary yellow". The complementary substitutional relation between adjacent hues was pointed out; as yellow increases red decreases or, alternatively, green decreases as yellow increases. The unitary yellow was identified as "100 yellow". With the stimulus set to a position that elicited a mostly reddish hue, the observer was asked to produce a hue that was 50 yellow/50 red; then 75 yellow/25 red, etc. The same thing was done with greenish-yellow hues. This was repeated a number of times with other numbers and the experimenter adjusted the stimulus a few times and asked for magnitude estimates. After pointing out the logical similarity between these operations and what had been done earlier for lightness - stressing that it was also possible to abstract hue from the total percept - the luminance of the stimulus was altered and more magnitude estimates of hue were made.

The same process was then repeated for unitary red, green, and blue hues. In each case, the observer performed magnitude productions and estimations of the proportions of unitary hues for stimuli of different luminance factors. He saw that there could be four unitary hues. Further, he experienced their perception. He learned to identify them as red, green, yellow, and blue. He found that hue could be abstracted from the total color perception. He learned to attach magnitude numbers to the hue proportions that he perceived. In short, each observer learned to scale hue according to the experimental paradigm.

Finally, saturation was addressed. This time the stimulus knob controlled colorimetric purity with no change in luminance or dominant wavelength. The dominant wavelength of the first series was chosen to elicit a reddish hue. Luminance factor was fixed at 0.20. The observer was permitted to explore changes in appearance that resulted from his adjustment of the stimulus. He found that he could adjust the stimulus to a condition where it appeared completely gray; where it had no trace of hue. He found that he could adjust the knob to produce a condition where the sample no longer appeared to be a surface color but was, instead, a luminous-appearing object. He saw that there were many adjustments between these extremes where the color appearance varied in ways that could not be described as changes in lightness or in hue. He was told that these new variations would be called saturation. Then the observer was asked to adjust the stimulus until he could see no trace of hue in the sample. This was identified as zero saturation. The logical similarity of this concept and zero lightness and zero hue was discussed. He was then asked to adjust the stimulus until the sample appeared neither luminous nor gray-containing; the point at which an abrupt change from the surface mode of appearance to the luminous mode occurs. The experimenter then pointed out that one form of relative saturation might be considered by assigning a modulus of 100 to this appearance, in the same manner that white was said to be 100 or a unitary hue was 100. The observer then scaled relative saturation by both magnitude production and estimation. In a manner analogous to that in which lightness and brightness were distinguished, the observer was also taught to distinguish between relative and absolute saturation. That is, he was told that the relative saturation was merely a proportion of chromatic content perceived relative to the perceived saturation of a reference perception. As that relative chromatic content increased, the achromatic (or gray) content decreased. He was instructed to use the term relative saturation only where both hue and grayness could be seen. Then with the stimulus adjusted so that it did not evoke a gray response (i.e., so that it appeared distinctly luminous) he was asked to assign a number, N, of his own choice to its saturation in terms of all conceivable saturations that he could imagine. He was then asked to turn the knob until the sample had a saturation of $\frac{1}{2}$N. But that stimulus usually appeared to contain gray, so it could be scaled as relative saturation as well. He found that the relative saturation magnitude (M) was not equal to the absolute saturation magnitude ($\frac{1}{2}$N). The distinction between relative and absolute attributes was again repeated. The observer then estimated the absolute saturation magnitudes of several stimuli that were presented by the experimenter.

Finally, the luminance factor was altered and more magnitudes of absolute saturation were estimated.

The process was then repeated with greenish and bluish stimuli; and certain other hues for some of the observers. Each observer learned from this series of observations that he could identify saturation, distinguish between relative and absolute saturation - seeing that not only did the two kinds of scales yield different numbers for a given hue, but also that 100 relative saturation for different hues had different absolute saturations from one another - and he could scale both attributes according to the same kind of scheme that he had brought to bear on the analysis of lightness, brightness, and hue.

At the end of the training period, the experimenter reviewed and summarized what had been done in the same sequence in which the work was carried out. Particular emphasis was placed on hue and absolute saturation. Every observer indicated that he was satisfied that he knew what was to be asked of him in performing the experiment. The three observers who had some moderate experience in scaling each independently volunteered that for the first time they felt that they understood clearly what was meant by 'saturation' and would now know how to scale it with a certainty they had not enjoyed before. The two completely inexperienced observers each offered such comments as "it's much easier than I thought it would be" and "if that's all there is to it, I'm sure I can do it". In substance, an air of confidence was generated.

The confidence of observers on completing the training phase suggested that the exercise had been helpful to them. As will become apparent later in the results, it also appears to have been successful in yielding precise and consistent data during the main experiment.

After this preparation, the observers performed magnitude estimations in the main experiment. Each observational session was not more than one hour's duration. The first twenty minutes of each session was used for adapting to the illumination condition under test. Before commencing with scaling of the test samples, the appearance of the surround was checked to make sure it was white; the surround was scaled two more times during the course of each session as a control. Then the observer was reminded of what was to be scaled and he was instructed as follows:

> "You will be presented with a series of samples in irregular order. They will be flashed in front of you at intervals. Your task will be to tell me what hue and absolute saturation you see. You may take as long as necessary - that is, use as many flashes as you wish - in order to satisfy yourself that you are able to describe the hue and absolute saturation to your satisfaction. Please describe them by assigning numbers to represent your subjective impressions. There are no constraints on the numbers that you may use for absolute saturation. But remember that hue should be described as a proportion of two neighboring unitary hues - red, green, yellow, blue - stating the proportions for both unitary hues. First decide whether or not you perceive any hue at all. If not, please reply 'neutral'. On the other hand, if the sample does not appear neutral - that is, neither white, nor gray, nor black - then decide which of the four unitary hues predominates. Next decide whether or not you see a trace of any other unitary hue. If so, identify it. Finally, estimate the proportions in which the two hues stand. When you have done that, please tell me what the hues and their proportions are. It will be helpful if you will state the predominant hue first. After you have scaled hue in this way, next direct your attention to the absolute saturation. Assign any reasonable number to the saturation of the first sample that you see. That is, use any number that you feel represents the absolute saturation of that first sample. You may use any number at all, but satisfy yourself that you are 'comfortable' with it as representing the absolute saturation in terms of all your past experience. After you have told me what the number is,

I will let you look at the first sample for a little while longer. Please try to remember its appearance and the number that you used to describe its saturation. Then assign successive numbers to the saturations of subsequent samples in a consistent manner to represent your subjective impressions. Are there any questions?"

These instructions were given to each observer before every session. In practice, on a very few occasions, some problem or inconsistency would arise during the session and further colloquy would be required to clear it up. For example, two observers once responded with 'brown' for stimuli of the lowest luminance factor, rather than some proportion of unitary hues. At this point the experimenter said: "That is one way of describing what you see. But remember we have decided to describe all hues as proportions of unitary hues; red, green, yellow, blue. 'Brown' is not one of our hue names. Now try to ignore the lightness and the saturation of this sample and concentrate on hue alone. Do you see any hue in it? What hue seems to predominate? Is there any other hue present? What is it? Then in what proportions do they stand?" In other words, if the observer indicated any confusion, the experimenter simply repeated those portions of the instructions that applied to the area of confusion in question. The necessity for such action was very rare.

All stimuli were presented in three different quasi-random orders a total of three times during each session. The observer scaled both hue and saturation for each presentation of a sample.

A selected subgroup of observers also conducted more extensive magnitude production work for hue, saturation, lightness, and brightness. That same subgroup also made magnitude estimates of the 24 stimuli under conditions of dark adaptation.

Summary of design and key.

The attributes chosen for evaluation were: (1) relative hue, (2) absolute saturation, (3) lightness, and (4) brightness.

Hue was scaled by the method of constant sum (Comrey 1950)[67] as proportions of adjacent unitary hues.

The attribute which is called 'saturation' here is the same concept as that labeled 'colorfulness' by Hunt (1976)[159]. In absolute form, saturation represents an attribute of color sensation according to which a sample appears to exhibit more or less chromatic color. That is the same definition used by Hunt for colorfulness. The term saturation is used by him to identify a relative form of colorfulness; viz., colorfulness judged in proportion to sample brightness. Colorfulness is a new term. Despite the fact that it may help to clarify this conceptually troublesome dimension, the word saturation has a much longer history of use and was chosen for this experiment quite some time before Hunt's proposal. Saturation - the word and the concept - has a reasonably clear operational definition in this experiment. Since it was used throughout the work, I will continue to use it in this description of the research, but with the caveat lector: saturation is that attribute of a color sensation according to which a sample appears to exhibit more or less chromatic color. This attribute was scaled by unconstrained numerosity.

Lightness was defined as that attribute of a chromatic or achromatic perceived color according to which a gray-containing sample appears lighter or darker; i.e., it appears to reflect more or less light. It was scaled relative to the lightness of the surround which was taken to have a lightness of 100.

In one phase of the experiment, brightness - that attribute of a chromatic or achromatic color perception according to which a sample appears more or less intensive - was also scaled by unconstrained numerosity.

Both magnitude estimation and magnitude production scaling was conducted. Details of the experimental phases for the various conditions studied are set forth in the following paragraphs. Table VII serves as a key to these phases.

The primary stimulus factors affecting chromatic

- -

Table VII.

Key to Experimental Phases

Phase	Test Lum	Sur Lum	Lum Ftr	K	No. O's	No. Observatns. Hue	Sat	Ltns/ Brtns
Mag.Est.:								
1	200	1,000	0.20	6,500	7	504	504	0
2	200	1,000	0.20	4,400	7	504	504	0
3	200	1,000	0.20	2,856	7	504	504	0
4	430	1,000	0.43	6,500	3	216	216	0
5	430	1,000	0.43	2,856	1	216	216	0
6	66	1,000	0.07	6,500	3	216	216	0
7	66	1,000	0.07	2,856	1	216	216	0
8	100	500	0.20	6,500	7	504	504	0
9	100	500	0.20	2,856	7	504	504	0
10	40	200	0.20	6,500	7	504	504	0
11	40	200	0.20	2,856	7	504	504	0
12	200	0	-	-	3	108	108	108
Mag.Prod.:								
13	200	1,000	(var.)	6,500	7	56-168	28-84	28-84
14	200	1,000	(var.)	6,500	4	240	120	420

Grand total of observations: 10,112

- -

adaptation used in this experiment were:

(1) correlated color temperature

(2) luminance factor of sample stimuli

(3) effective illuminance expressed as surround luminance.

Three correlated color temperatures were used: (a) nominally 6,500 K, (b) nominally 4,400 K, and (c) nominally 2,856 K; corresponding to the chromaticities of CIE Illuminants D_{65}, D_{44}, and A respectively. The names of those CIE Illuminants will be used here for convenience in referring to the test illuminants.

Three luminance factors were chosen for the D_{65} and A conditions: (a) approximately 0.07, (b) 0.20, and (c) 0.43; corresponding to Munsell Values of 3, 5, and 7 respectively. A luminance factor of 0.20 was used for the D_{44} condition.

Three effective illuminances were used for the D_{65} and A conditions. These produced surround luminances of (a) 200 $cd \cdot m^{-2}$, (b) 500 $cd \cdot m^{-2}$, and (c) 1,000 $cd \cdot m^{-2}$. Only the 1,000 $cd \cdot m^{-2}$ surround was used for the D_{44} condition.

A subsidiary phase of the experiment involved a condition in which the samples had luminances of 200 $cd \cdot m^{-2}$ and were presented with an effectively zero luminance (dark) surround.

The foregoing information is summarized in Table VII. That table indicates the four major phases of magnitude estimation experimentation:

1) The effect of color temperature , consisting of all 7 observers scaling hue and saturation (with 3 replications for each of 24 stimuli) under D_{65}, D_{44}, and A conditions. In each case the surround was 1,000 $cd \cdot m^{-2}$ and the sample luminance was 200 $cd \cdot m^{-2}$ (a luminance factor of 0.20). A total of 3,024 observations were made in this phase. The experiments are identified in Table VII as numbers 1, 2, and 3.

2) The effect of luminance factor, consisting of 3 observers scaling hue and saturation additionally for all stimuli under D_{65} and 1 observer using A as well for luminance factors of 0.43 and 0.07. These data were used in conjunction with the same observers' data for luminance factor 0.20 samples under the otherwise same conditions with a 1,000 $cd \cdot m^{-2}$ surround to determine the influence of luminance factor on hue and saturation. The additional data collected in this phase amounted to 1,728 observations. The experiments are identified in Table VII as numbers 4, 5, 6, and 7.

3) The effect of illuminance, consisting of all 7 observers scaling hue and saturation in addition for D_{65} and A illuminants with sample luminance factor 0.20 at surround luminances of 500 and 200 $cd \cdot m^{-2}$. These data were used in conjunction with the observers' data for the same luminance factor samples in a 1,000 $cd \cdot m^{-2}$ surround to determine the influence on hue and saturation of illuminance. The additional data collected in this phase amounted to 4,032 observations. The experi-

ments are identified in Table VII as numbers 8, 9, 10, and 11.

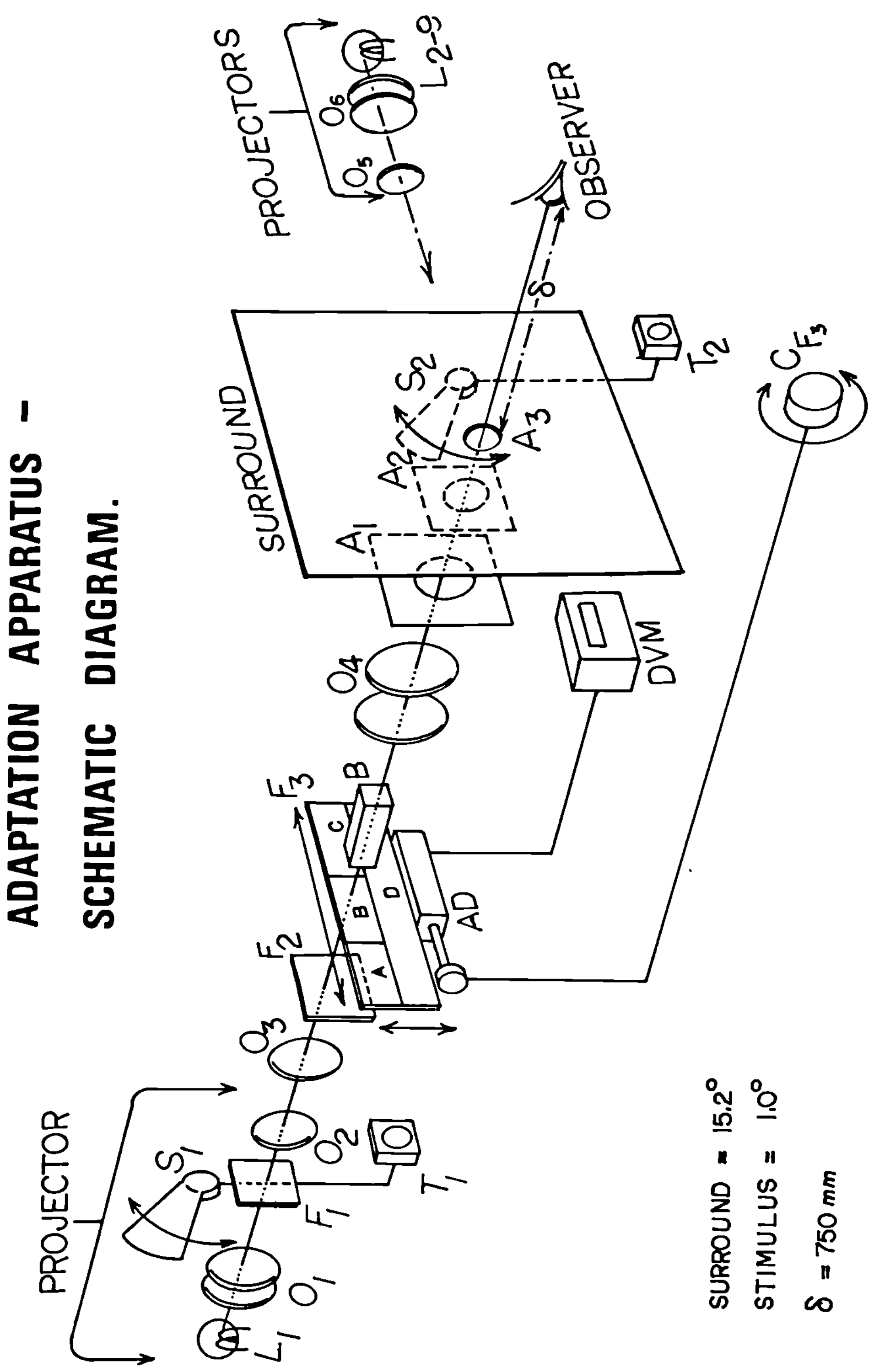
4) The <u>effect of induction</u> consisting of 3 observers scaling hue and saturation together with brightness for all samples at 200 $cd \cdot m^{-2}$ presented in a zero luminance (dark) surround. These data were compared with data for the samples at the same luminances with surrounds of 1,000 $cd \cdot m^{-2}$ to determine the influence of induction by the surround on hue and saturation. The brightness data were compared with lightness data derived by magnitude production with the 1,000 $cd \cdot m^{-2}$ surround to examine the influence of surround induction on the shapes of the relative brightness curves. The additional data collected in this phase of the experiment amounted to 324 observations. The experiment is identified in Table VII as number 12.

The total number of magnitude estimations was, then, 9,108. They relate primarily to variations in hue and saturation over changes in the adaptation factors studied. In any one experiment (numbers 1 through 12) the 24 samples were all approximately equal in luminance. Therefore, the lightnesses and brightnesses they elicited were constant in any one experiment. Small differences in lightness and brightness of individual samples existed as a consequence of the Helmholtz-Kohlrausch effect. Primary study of lightness and brightness was carried out in the magnitude estimation phases of the experiment (numbers 13 and 14 in Table VII) in conjunction with training and supplementary experiments. A total of 1,004 magnitude productions were recorded. Thus, the grand total of observations was 10,112.

III. Experimental Apparatus

The experimental apparatus was designed and constructed to permit both magnitude production and estimation experiments to be carried out according to the design elaborated above. The essential features of that apparatus are illustrated in Figure 6. Basically, it consisted of a stimulus source, an integrating tunnel, and an illuminated surround with a central aperture through which the output end of the integrating tunnel was uniformly imaged at infinity. The central aperture was sharply defined and the homogeneous field that filled it was always at a luminance well below that of the surround, so that all test stimuli were seen in the surface mode of appearance.

The stimulus source consisted of a modified 750 watt Kodak Carousel Projector. The relative spectral power over wavelength of that system (including all optical modulators as measured through aperture A_3) is listed in Appendix D. The projector lamp, L_1, was operated at 95 per cent of nominal current rating from an electronically regulated power supply providing ±0.1 per cent regulation. Condenser lenses O_1 illuminated a stimulus filter stage, F_1, used in the magnitude estimation experiments. The combination of objectives O_2 and O_3 provided a collimated beam for illuminating the entrance surface of mirror tunnel B. The tunnel consisted of a hollow, extruded, polished aluminum bar with opalized Perspex ends. The tunnel was square in cross-section (2 cm on a side) and its length was four times as long as its side. Its optical integration characteristics were excellent. An enlarged image of the exit surface was relayed by objectives O_4 to the aperture A_3. The observer was positioned by a head and chin rest so that the relayed image filled A_3 and was seen to be a homogeneous display. Photometric uniformity of the aerial image at the observer's position was high enough so that variations could not be measured with available equipment. Baffles A_1 and A_2 were located to minimize stray light contributions to the stimulus radiance. Another baffle (not shown in



ADAPTATION APPARATUS -
SCHEMATIC DIAGRAM.
PROJECTOR
PROJECTORS
SURROUND
OBSERVER
DVM
AD
SURROUND = 15.2°
STIMULUS = 1.0°
δ = 750 mm

Figure 6

Figure 6) was located between the observer and the surround in such a way as to restrict his view to about 70^{o} angular subtense.

The surround consisted of reinforced, 1 mm thick cardboard of high and approximately spectrally nonselective diffuse reflectance surface. It subtended 15.2^{o} on all sides. In turn, the surround periphery consisted of black velvet paper subtending and additional 60^{o} annulus on each side. The entire extreme periphery (beyond the black velvet) was baffled with black paper. The central aperture, A_3, was circular with a subtense of 1^{o}. Its edges were cut on a bevel to ensure singular and sharp demarcation between surround and sample areas.

The surround was illuminated by eight 150 watt Plus Projectors. All eight projectors were operated from a main voltage line; but time of operation was chosen such that measured variations in voltage did not exceed ±2 per cent of mean value. Both total and spectral irradiance from each of the eight surround projectors could be altered independently. This permitted a close chromaticity match to be made to the aim surround chromaticity. Those matches were achieved by covering the projector lenses with various combinations of Cinemoid plastic filters. The color mixture of the combined surround flux was partly subtractive and partly additive. The surround illumination consisted of an additive mixture of flux from all surround projectors. Relative spectral power distributions of the light reflected from the surround surface are listed in Appendix A for the D_{65} and A illumination conditions. Spectral power was not measured for the D_{44} condition. In all three cases, the aim was to match the chromaticity coordinates of the CIE aim illuminants as closely as possible. Table VIII indicates the extent to which this aim was met.

A baffle between the observer and the surround prevented him from seeing any of the projectors.

A rotary solenoid activated a paddle shutter, S_2. Solenoid operation was controlled by timer T_2. The

Table VIII

Comparison of Aim and Actual Chromaticities
(Surround)

CIE Ill. A	CIE Ill. D_{44}	CIE Ill. D_{65}
x = .4476	x = .3454	x = .3127
y = .4074	y = .3584	y = .3290
Test Ill. A	**Test Ill. D_{44}**	**Test Ill. D_{65}**
x = .4467	x = .3453	x = .3140
y = .4072	y = .3586	y = .3276

shutter was located immediately behind the surround in such a way that its front surface was in contact with the rear surface of the surround. The front surface of the shutter was made of the same material as that of the front surface of the surround so that when the shutter was in the closed position it appeared to be a continuation of the surround. An air vane was positioned on the solenoid to create a draft when it rotated, thereby separating the paddle front surface and surround rear surface during shutter transit to avoid scatching the shutter. Location of the solenoid, shutter length and breadth, were jointly chosen to allow the sample to beam to open (or close) completely within 50 milliseconds. Thus, the change from sample to no sample present appeared to occur instantaneously.

Magnitude production stimuli were controlled by positioning a multi-part filter, F_3, in front of the entrance to the integrating tunnel. The observer was able to operate a remote adjustment, C_{F3}, that varied the position of filter F_3 along a horizontal dimension. Various filter combinations were used for F_3 depending upon what was being scaled; dominant wavelength differences for hue, or purity differences for saturation. A logarithmic tapered opaque occluder was used in the F_3 position for scaling lightness and brightness. A 1 megohm, log-taper, slide resister was welded to the

F_3 filter carrier so that exact position was represented by the impedance across resister AD. The digital meter DVM was connected to this circuit so that the experimenter was provided with a display of F_3 filter position without the observer being aware of it. Filter position was calibrated in terms of resistance and corresponding tristimulus values or luminance attenuation according to the phase of magnitude production under study.

The filter F_3 was removed for magnitude estimation work. Magnitude estimation stimuli were introduced by the projector slide changing mechanism at position F_1. A remote control, T_1, was available for the experimenter to change stimuli. This control was operated manually after the observer had provided his response; during the the occlusion semi-cycle of S_2. A second shutter, S_1, was simultaneously activated inside the projector to prevent high light levels from passing through the stimulus beam. Spectral transmittances of the 24 filters used in magnitude estimation are listed in Appendix C. Chromaticity coordinates of the 24 stimuli (filters, source, and all stimulus beam components) as seen by the observer are given in Appendix B.

The stimulus filters consisted of various combinations of (a) Lovibond glass filters, (b) Chance glass filters, and (c) Cinemoid plastic filters. The resultant stimuli provided the gamut of chromaticities listed in Appendix B and illustrated in Figure 4 (page 82).

Filter position F_2 was located between the stimulus projector and tunnel B. It was used to position calibrated Wratten (carbon) Neutral Density Filters in the beam in order to adjust the luminance factor of sample stimuli. In addition, F_2 was used to introduce chromatic filters and color temperature conversion filters during the scaling of lightness and brightness. The conversion filters were such as to cause sample and surround to match in chromaticity.

Measurement, calibration and monitoring of all stimuli was accomplished in two ways. Initial measurement and calibration were carried out with the aid of a Bausch and Lomb Spectronic 505 Spectrophotometer.

Monitoring of stimuli was done with a calibrated Photo Research Spot Brightness Meter UBD/No. A322 which was modified for relative tristimulus measurement.

The spectral transmittances of all filters were measured on the Spectronic 505 instrument modified for digital output. In addition, all lenses and the integrating tunnel were measured on this instrument. In each case, the 505 beam geometry was adjusted to simulate the optical geometry appropriate to the elements under consideration. A three-week base-period of calibration data gathered on the 505 shows a standard deviation of spectral transmittance of ±0.2 per cent. That figure represents the precision of repeat measurements from day to day. The question of accuracy is more difficult to evaluate. The United States National Bureau of Standards attaches uncertainty values to the calibration of its 2100 series filter glasses of 0.2 to 0.5 per cent transmittance for absolute calibration. The United Kingdom's National Physical Laboratory sets uncertainties of 0.15 to 0.25 per cent reflectance on the absolute calibration of the British Ceramic Society tiles. Since these uncertainties are of the same order of magnitude as the precision of measurements observed during the base-period, the most that can be said about accuracy of spectral modulation measurements obtained here is that they appear to be satisfactory. Analog output measurements of the wavelength accuracy of the 505 instrument used showed a variation in absorption peaks of didymium glass of about 0.9 nm standard deviation and 1.3 nm maximum. Since that figure for standard deviation is within the variability encountered with repeat measurements carried out in immediate succession, it is impossible to assign it either to instrumental accuracy or to analog precision in positioning graph paper. It seems reasonable to state that both precision and accuracy of the 505 instrument used was satisfactory for the task at hand.

The Spectronic 505 was also used to obtain relative spectral irradiance measurements of both stimulus and surround projectors. This was accomplished by removing the instrument's light source and substituting a projector. In addition, a calibrated tungsten color temperature lamp was also measured. Ratios of relative irradiances (with respect to the assumed spectral emittances of the calibrated lamp) provided a measure of relative spectral power distributions of the test sources. These data were used in conjunction with the spectral transmittances of all elements in a stimulus beam to compute the relative spectral powers listed in Appendices A and D.

Final measurements, and continuing monitor data, were obtained with the use of the Photo Research UBD instrument. This instrument permits measurements in four modes; three of which were used here: (1) 'P' mode for luminance and Y tristimulus analog, (2) 'R' mode for X tristimulus analog, and (3) 'B' mode for Z and X' tristimulus analogs. Factory calibrations of these three modes were provided by Photo Research. Calculation of CIE 1931 $\bar{x},\bar{y},\bar{z}$ values from mathematical combinations of P,R,B outputs results in a set of three spectral error functions. These are listed in Appendix E. The three functions represent spectral response errors that influence determination of CIE 1931 chromaticity coordinates. The error integrals from Appendix E are $\bar{e}_{\bar{x}}$ = 0.0245, $\bar{e}_{\bar{y}}$ = 0.0123, and $\bar{e}_{\bar{z}}$ = 0.0240. For an equal energy source and spectrally nonselective samples, this amounts to errors of 2.41% in $\bar{x}$, 2.01% in $\bar{y}$ and 2.50% in $\bar{z}$. Maximum errors at any wavelength are -0.0885 in $\bar{x}$, +0.0915 in $\bar{y}$, and -0.1929 in $\bar{z}$. Actual errors for typically selective samples will be intermediate between these extremes. However, since the error functions are known and the spectral data from the 505 measurements are available, it is not necessary to accept the error integrals of Appendix E as limiting factors. It is possible, given these two sets of information, to practice difference colorimetry according to accepted colorimetric practice (v., Judd and Wyszecki 1975, pp.211-219)[190]. Provided that the 505 measurements are proportional or nearly so to the true values of spectral radiances, then difference colorimetry will eliminate or minimize the error integrals associated with mismatched responses and distribution coefficients. Repeated measurements for monitoring purposes are satisfactory provided only that repeated readings of the same spectral modulators are proportional for each wavelength. Accordingly, the UBD telescopic instrument was used at the observer's position to measure and monitor luminance and chromaticity of both sample beam and surround by the method of difference colorimetry.

A series of data was generated over a two week period with that technique in order to estimate the precision that could be expected by such measurements. Table IX shows the results of this test.

Table IX

Precision of UBD/No. A322 Used as a Photometer/Colorimeter

Parameter		Standard Deviation	Per Cent Error
'P' mode		0.45	0.05
'R' mode		0.55	0.11
'B' mode		0.55	0.17
CIE 1931 chromaticity	(x)	0.00035	-
	(y)	0.00033	-

The luminances and chromaticities of the surround as illuminated by individual surround projectors with their filters in position were measured after every 4 hours of operation. It was necessary to replace two filters during the course of the experiments. Magnitude estimation stimuli were measured after every 2 hours of operation. No filters needed to be replaced. Control limits for replacement were arbitrarily set at ten times the standard deviation of chromaticity and luminance differences of 2 per cent were used for upper limits of photometric stability. It will be seen from this that both surrounds and test stimuli remained essentially constant throughout the experiment.

The sample stimuli - measured telescopically from the observer's position - were as uniform over their areas as could be measured. There were, however, slight variations in both luminance and chromaticity over areas of the surround. The average surround luminance for all three illuminant-conditions (D_{65},D_{44},A) was actually 1,066.7 $cd \cdot m^{-2}$. Luminances provided by each of the sources, together with the standard deviations over the central 13° of the 15.2° surround, were: (D_{65}) 1,080 ±13.0 $cd \cdot m^{-2}$, (D_{44}) 1,030 ±14.5 $cd \cdot m^{-2}$, and (A) 1,090 ±11.8 $cd \cdot m^{-2}$. Thus, the deviations from average surround luminance among the three conditions was +1% for D_{65}, -3% for D_{44}, and +2% for A. These levels are all referred to as 1,000 $cd \cdot m^{-2}$. The two lower surround luminance conditions were obtained by interposing neutral filters between the observer and the surround plane. Uniformity and deviations from average luminance were proportionately the same as above. The effective mean luminances were actually 504.3 $cd \cdot m^{-2}$ and 199.0 $cd \cdot m^{-2}$; nominally 500 and 200 $cd \cdot m^{-2}$ respectively.

Since the surround chromaticity was derived in part from additive mixtures of the flux from the eight surround projectors, nonuniformities of illumination also gave rise to some variations in correlated color temperature over surround area. The mean correlated color temperature of the D_{65} condition was 6,510 K (153.6 mireds) with variations over the central 13° diameter area of ±3.0 mireds; i.e., from 6,385 K to 6,640 K. The mean for the D_{44} condition was 4,400 K (227.3 mireds) ±4.6 mireds; i.e., from 4,313 K to 4,491 K. Finally, the mean for A was 2,840 K (352.1 mireds) ±2.1 mireds; i.e., 2,823 K to 2,857 K. Thus, the surround color temperatures were close to their nominal values. They were also reasonably uniform over area; viz., within 2 per cent variation in mireds.

IV. Results

The complete experiment consisted of a reasonably large number of phases. It will aid clarity of exposition to present the experimental results according to major effects on chromatic adaptation. First there will be an explanatory section describing the procedures used to normalize data and a summary of their precision. Then subsequent sections will describes the effects on hue and saturation of (a) correlated color temperature, (b) luminance factor, and (c) illuminance. Finally, there will be a section dealing with lightness and brightness variations induced by changes in adaptation.

Data normalization and variability.

Unconstrained numerosity was used in scaling absolute saturation by magnitude estimation and production. The appropriate central tendency measure in such cases is the geometric mean. Computation of the geometric mean to determine the average observer's results, automatically establishes a basis for normalizing the results of individual's data. If the individual psychophysical functions are either logarithmic or power in form, they will each be related to the geometric mean function by a power transform (Bartleson 1968b)[17]. That was, in fact, the case for magnitude scales of saturation provided by all 7 observers in these experiments. Figure 7 shows a representative set of relationships for the A adaptation condition (experiment 3 in Table VII on page 101). That graph illustrates the fact that individual saturation functions ($\bar{S}_i$) are each related to their common geometric mean function ($\bar{S}_G$) through a power transform. The individual functions are arbitrarily separated along the abscissa of Figure 7 for clarity. Since the coordinates of the graph are logarithmic, the slopes of the lines correspond to values of exponents in those relations. The slopes are not all equal. That means that some observers used a greater range of numbers than did others. The slope for observer D, for instance, has the highest value. The slope for observer F is lowest. Therefore, observer D was more con-

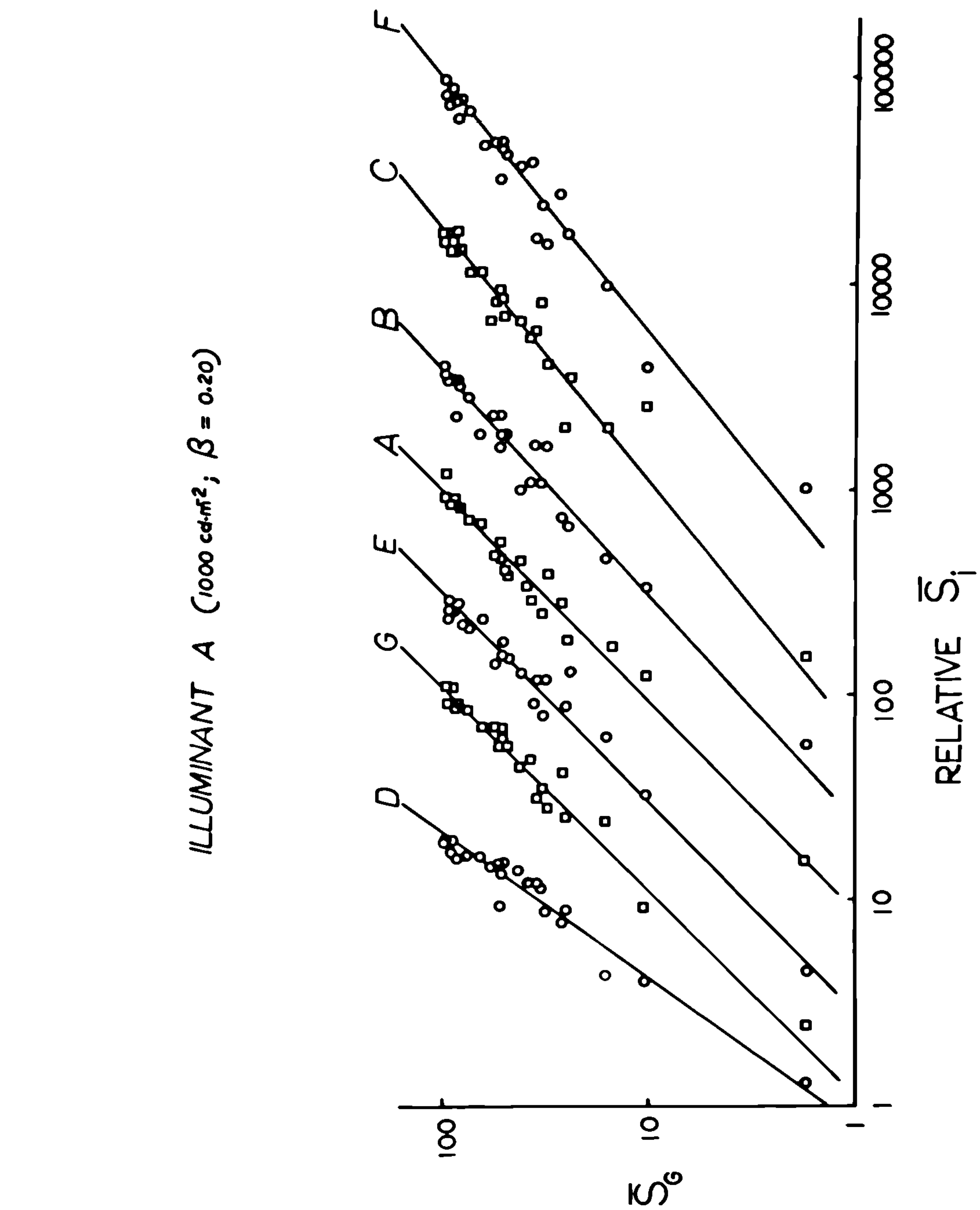

ILLUMINANT A (1000 cd·m²; β = 0.20)
D
G
E
A
B
C
F
100
10
1
$\bar{S}_G$
1
10
100
1000
10000
100000
RELATIVE $\bar{S}_i$

Figure 7

servative in his use of numbers than was observer F.

Regardless of the actual exponent for a given observer, his results will be consistent for cross-comparison if he adopts a uniform criterion of scaling for all trials. In other words, the results have internal validity if the individual power functions of a given observer always relate to the geometric mean function by the same or nearly the same exponent. Thus, a measure of consistency of compression among sessions for each of the observers is also an index of internal validity. Table X lists the constants of the power equations relating individual saturation functions to the geometric mean function together with coefficients of determination for the power equations.[101]

Table X

Conversions to Common Saturation

$(y = ax^b)$

Conditions	Observers A	B	C	D	E	F	G
Exponents, b:							
D_{65}	0.74	0.95	0.80	1.68	1.12	0.85	1.09
D_{44}	0.73	0.85	0.87	1.54	0.98	0.83	0.98
A	0.75	0.91	0.84	1.39	0.98	0.82	1.01
Scale Factors, a:							
D_{65}	2.43	0.84	1.62	0.09	0.80	2.29	0.82
D_{44}	2.57	1.82	1.00	0.14	1.17	2.24	1.05
A	2.40	1.32	1.40	0.21	1.38	2.38	1.20
Coefficient of Determination, r^2:							
D_{65}	0.93	0.89	0.90	0.74	0.79	0.93	0.98
D_{44}	0.92	0.85	0.89	0.80	0.93	0.96	0.94
A	0.97	0.96	0.95	0.95	0.96	0.96	0.97

The coefficient of determination may have a value between 0 and 1. The closer it is to unity, the greater the confidence that the computed relationship is correct. Generally, the less the scatter of data, the higher will be the coefficient of determination. However, even with scatterless data, its value will be low if the form of function fitted to the data is inappropriate to the underlying relationship. Values between about 0.7 and 0.8 are usually considered 'good' and values above 0.9 are said to be 'excellent' determinations of the 'goodness-of-fit' for such functions. Table X indicates that all the relationships between individuals and their common geometric means, over all three illumination conditions, were good to excellent.

The scale factors (a in Table X) merely indicate the multiplicative constants used in each session by observers. The fact that they vary among observers means that they each chose a somewhat different modulus. Variations of scale factors for any one observer reflects slight differences in the modulus he used for each session.

It is really the exponent (b in Table X), representing scale compression, that is the best index of how an observer used numbers. Again, variations in values of exponents among observers merely indicates differences of individual compression. However, the variation of exponent value over sessions for any one observer shows how consistent he was in using numbers. Table X indicates that all 7 observers showed a high degree of consistency in this regard. Observer A was most consistent over sessions; from 0.73 to 0.75, a range of only 2.7 per cent variation in exponent. Observer D was least consistent; 1.39 to 1.68. But this is still only an 18.8 per cent variation in exponent value. On average, the variation in range of exponents over sessions was 8.9 per cent. That is a very good figure for magnitude scaling (v., J.C. Stevens and Guirao 1964; L.E. Marks 1974a; S.S. Stevens 1975)[312,242,317]. Accordingly, the data for saturation scaling should be considered highly consistent among sessions and the geometric mean functions may be taken as a valid representation of the average responses of these 7 observers.

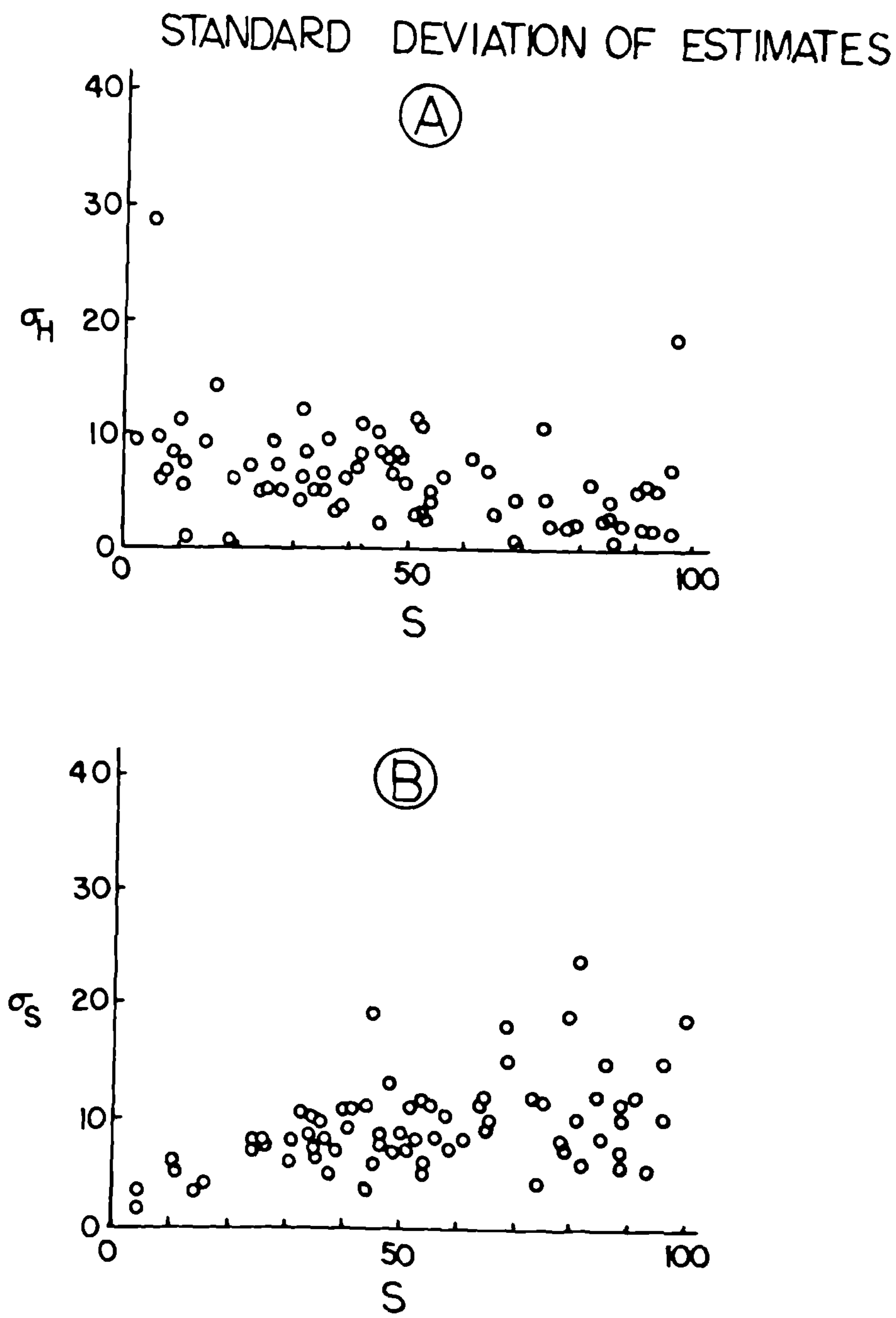
The power functions of Table X may be used to normalize the individual functions to values on a common saturation scale. The common scale then represents an unbiased response, the values of which may be subjected to reduction for ordinary statistics of moments such as mean and standard deviation. Appendix F tabulates the standard deviations - in per cent of response value - for each of the 24 stimuli over all sessions for each of the 7 observers plus the average observer. Both average standard deviations and mean probable errors are shown for each observer. The mean probable error represents the average deviation from mean such that 50 per cent of the observations may be expected to lie between the true mean and plus or minus the probable error (Fischer and Yates 1953)[101]. Mean probable errors for these experiments may be seen to lie between 5.5% and 25.4% with an average observer mean probable error of 12.8%. Since direct scaling data are often found to contain standard deviations of ±0.3 log units (up to 100% deviations), these figures of standard deviation at about 19% for the average observer should be considered very good.

The figures for saturation scaling variability do appear to distinguish among the observers according to their experience. The two observers (A and D) who were classed as highly experienced had the lowest mean probable errors; an average of 8.1%. The two observers (B and E) with no experience had the highest errors; an average of 24.8%. The average for observers with moderate experience was 13.1%. In all three cases, the variations about the class mean is less than the differences among classes. Thus, there seems to be a distinct difference among observers in terms of their ability to scale saturation precisely; and this difference is correlated with the extent of previous scaling experience. But considering the notorious difficulty encountered in scaling absolute saturation, even the roughly 25% mean probable errors of the inexperienced class is very good. This may be taken as one indication that the training program aided in obtaining precise results.

Hue was scaled as relative proportions of unitary hues by the method of constant sum. While the psychophysical functions may also be power ones here, numerosity was not completely unconstrained in the same way as for scaling saturation. Moduli of 0 and 100 were fixed. Thus, the relative hue responses of individuals may be subjected to arithmetic averaging. Under such conditions (fixed moduli for inherent anchors) it is assumed that differences in response values represent differences in physiological states of the organisms rather than differences in the way numbers are used. That assumption may be subjected to test.

Appendix F also lists the per cent standard deviations of hue responses for all 24 stimuli for each of the 7 observers and their common average observer. The mean probable errors for hue by individuals range from 0.9% to 2.6% with an average of 1.8%; very high precision. The mean probable error for the average observer is 3.7%. That figure is a little over two times as high as the average of the individual values. Thus, the observers differed from one another in their hue responses more than they varied over sessions. Although their anomalous quotients from the Nagel anomaloscope were all quite similar, the observers did perceive hue in systematically different ways. This will be seen later in summarizing the hue responses for various experimental phases, but it is also implied by the larger mean probable error for the average observer than for any of the individual observers. Again, however, both average and individual observers were able to scale hue with outstanding precision.

The data of Appendix F show that hue was more easily (or at least more precisely) scaled than saturation. Hue responses represent a complete hue circle ranging in value from 0 to 100. The four unitary hues were spaced at intervals of 25: red = 0 (or 100), yellow = 25, green = 50, and blue = 75. However, the observers scaled hue with 100 steps between adjacent unitaries. Accordingly, the mean probable errors for hue in Appendix F must be multiplied by a factor of 4 if they are to be compared directly with saturation errors. Thus, the average figure for individuals is about 7% for hue



STANDARD DEVIATION OF ESTIMATES
A
40
30
20
10
0
σ_H
0
50
100
S
B
40
30
20
10
0
σ_S
0
50
100
S

gure 8

compared with 13% for saturation. In very general terms, then, we may say that saturation was about twice as difficult to scale as hue.

Figure 8 provides graphical displays of the standard deviations of both hue and saturation over all three illuminant conditions for all 24 stimuli. The standard deviations of hue are plotted against saturation level in Figure 8a. There is a tendency for variability to be greater at low saturation. This is a reasonable and intuitively expected result. It is more difficult to assess the hue of a near-neutral sample than a highly chromatic one. Figure 8b indicates that standard deviations for saturation tend to increase with level of saturation. In other words, variability increases with level; a typical result for prothetic continua such as saturation.

The relatively low variability figures for both hue and saturation, together with the high consistency of individual scale relations over sessions, imply two things. First, the internal consistency of the results is satisfactorily high; even unusually high. Second, the initial training sessions served a useful purpose. Although a separate control session (without pretraining) was not conducted, the unusually high internal consistency for magnitude scaling together with the previously noted remarks of observers indicating their degrees of confidence, combine to suggest that the training sessions constituted a key phase in the experiment. Additional evidence of both internal and external consistency (i.e., validity) will be described at appropriate places in the following sections. Those sections will describe the results in terms of effects on color appearance of the various adaptation factors studied.

Effect of color temperature.

Hue and saturation were scaled by magnitude estimation in experiments 1, 2, and 3 of Table VII on page 101. Those experiments involved scaling by 7 observers of all 24 stimuli at a luminance factor of 0.20 (Munsell Value 5) with respect to surrounds of 1,000 cd$\cdot$m^{-2} for

3 illumination conditions: (1) D_{65}, (2) D_{44}, and (3) A. The results reflect the influence of color temperature on color appearance of invariant stimuli. Data for the 7 observers and the average observer are listed in Appendix G. Common scale values for hue and saturation are tabulated for each observer and stimulus in that appendix. The common scale values are normalized means of 3 trials for each stimulus. The average observer's data for saturation are geometric means of the individual raw data means. In some cases the arithmetic means of the common (normalized) scale values are slightly different from the geometric means listed. Those differences arise from minor discrepancies between normalized values and the 'true' common scale values. The discrepancies are associated with rounding errors in computation. They are generally insignificant.

Estimates for hue and saturation of the surrounds are also given in the tables of Appendix G. Saturation values less than 3 to 5 should be considered equivalent to zero (i.e., neutral) since that represents about the limiting scale resolution. Accordingly, it may be inferred from Appendix G that the surround appeared white to the average observer under all three conditions of adaptation.

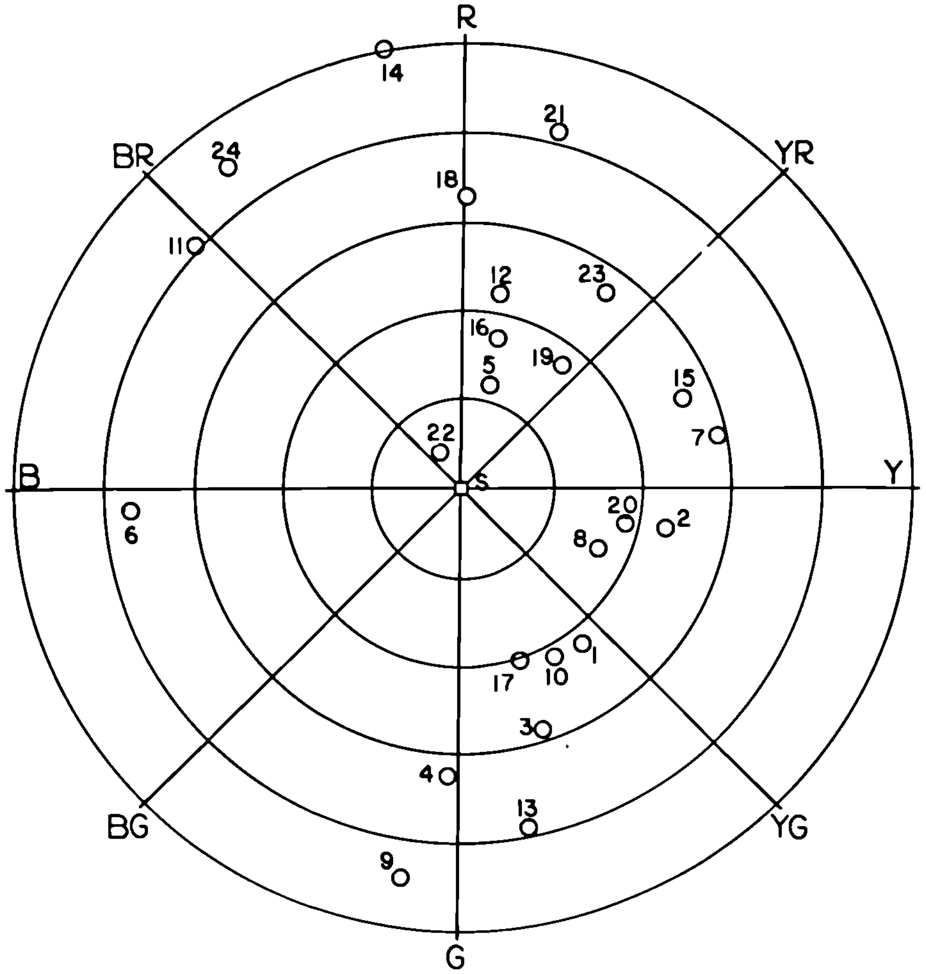
The data of Appendix G represent hue and absolute saturation. Hue numbers range from 0 to 100, corresponding to values on a hue circle from unitary red (at 0), through yellow (25), green (50), and blue (75) back to red (100). The circle is thus evenly divided in terms of hue proportions as angular extents. Saturation is represented in such a structure as radial displacements, with saturation ratios extending from zero to infinity. Accordingly, the results may be presented graphically on a planar color diagram in polar coordinates. The coordinates are perceptual. Although they are nonmetric according to criteria of additivity, they none-the-less provide a direct, graphic picture of the relationships of perceptual magnitudes for hue and saturation. Since all the points on such a diagram for the results of experiments 1 through 3 correspond to constant luminance, there are variations in brightness and lightness across the plane. It should therefore be considered a plane projection in uniform (magnitude) perceptual color space with uniformity in hue and saturation but not necessarily in lightness or brightness. For convenience of abbreviation, such a diagram will be referred to here as a 'response diagram'.

Figure 9 shows a response diagram for the results of Experiment 1, with D_{65} adaptation. The position of each of the 24 stimulus points on that response diagram provides a quantitative indication of the hue and saturation of every stimulus as perceived by the average observer. Stimulus 14, for example, was seen to be slightly bluish-red in hue with a relatively high saturation. On the other hand, stimulus 15 was seen to be reddish-yellow with much lower saturation.

The color appearances of these same stimuli under illuminant A adaptation conditions are illustrated in Figure 10. It may be seen from that response diagram that the appearance of stimulus 14 has not changed very much by adaptation to the lower color temperature illumination. However, stimulus 15 is now seen as a greenish-yellow at even lower saturation than was the case for D_{65} adaptation. Similar kinds of shifts in color appearance, brought about by changes in chromatic adaptation, may be evaluated for each of the other stimuli as well. Figure 11 facilitates the comparison. In that response diagram, the arrow-heads represent color appearances under A adaptation and arrow-tails correspond to appearances of the same stimuli under D_{65} adaptation. The lengths and orientations of the arrows differ depending upon their positions in the diagram.

One way of analyzing the color shift arrows of Figure 11 is in terms of the implied distortion to the symmetrical coordinates of the response diagram that would be required to maintain the same color appearance values for both conditions of adaptation. That is, how would the polar diagram have to be stretched or

ILLUMINANT D_{65} (1000 $cd \cdot m^{-2}$)



igure 9

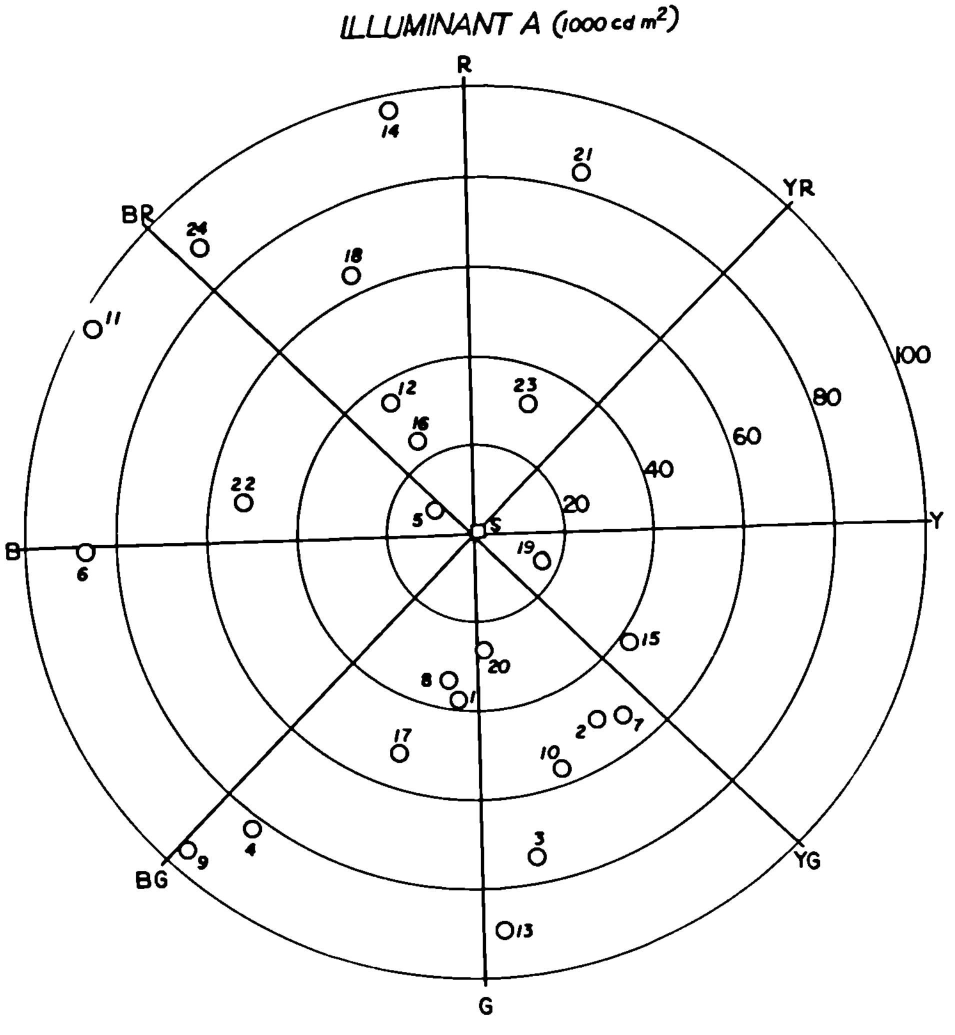

ILLUMINANT A (1000 cd m^2)
R
YR
Y
YG
G
BG
B
BR
S
20
40
60
80
100
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24

Figure 10

SHIFT FROM D_{65} TO A (1000 $cd \cdot m^{-2}$)

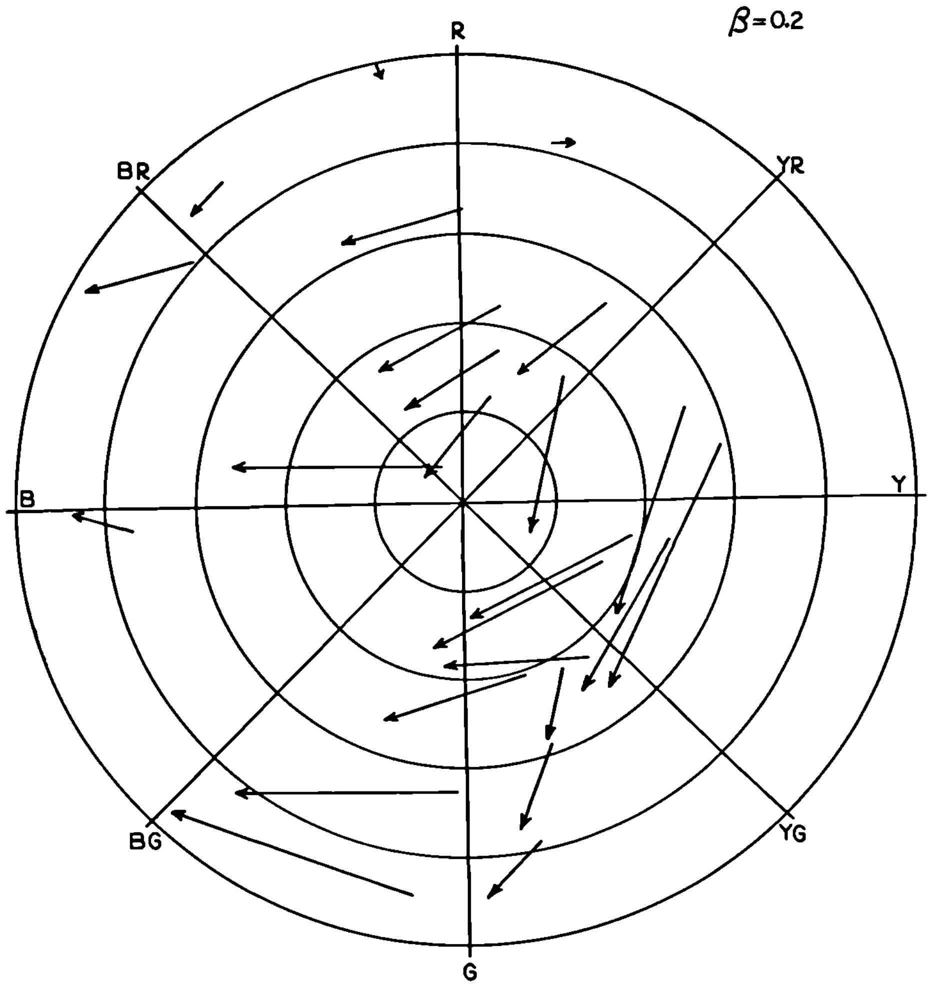
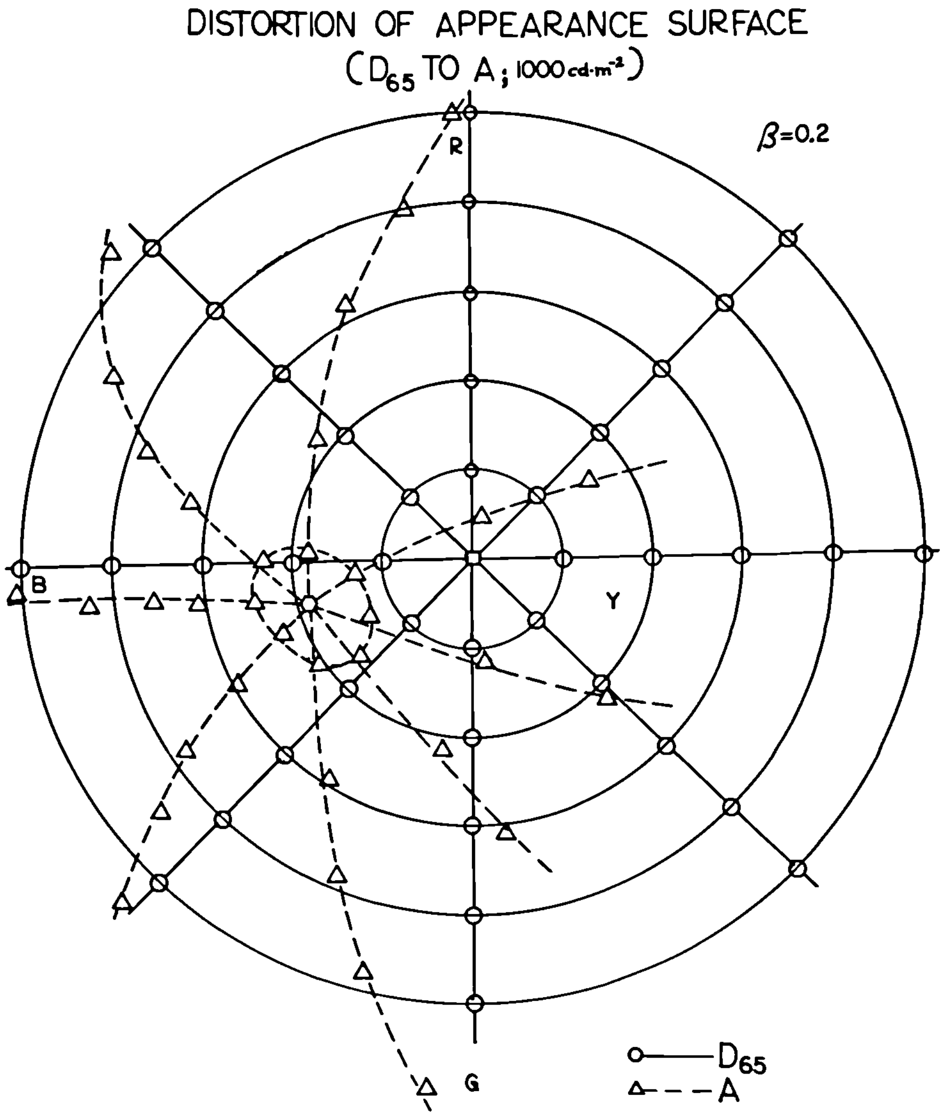


Figure 11

squeezed so that, on average, every stimulus would have the same numerical values for both D_{65} and A adaptation? Figure 12 gives an example of such a distortion surface. The solid contours represent an arbitrarily symmetrical D_{65} condition. Points shown as circles correspond to saturations of 20 through 100, in increments of 20, for each of the four unitary hues and their four intermediates. Each circular point corresponds to a triangular point of the same hue and saturation value but in a distorted coordinate system for A adaptation. The broken contours outline that distorted coordinate system. The contours were constructed visually, using a procedure analogous to the statistical method of least squares, in an attempt to normalize the color shifts of the invariant stimuli brought about by a change in adaptation from D_{65} to A.

Visual methods of fitting contours to points are the oldest and in some ways still the most reliable methods of extracting information from experimental results. "Physiologists are forever plotting the results of their experiments on graph paper for the very good reason that a graph enables the viewer to see at once the general trend of the results without being distracted by the actual numerical values of the individual observations... he is often not content to let (the data points) speak for themselves (so) he draws a smooth line through them... this commonplace act is a first-rate example of inductive reasoning" (Riggs 1963, pp.47-49)[278]. A good representation - often of complex variation - can be obtained with visual graph-fitting by bringing experience and common sense to bear on the problem. For these reasons, the response maps derived here have been constructed visually.

The distortion map of Figure 12 provides some advantage over methods for displaying adaptive shifts that have been used by other workers. In particular, all averaging and normalizing is carried out in response space; not in some distorted stimulus space intended to represent response relations. Helson et al (1952)[138] used a Munsell diagram for this purpose. Rowe (1972)[279]


DISTORTION OF APPEARANCE SURFACE
(D_{65} TO A; 1000 $cd{\cdot}m^{-2}$)
β=0.2
R
B
Y
G
D_{65}
A

igure 12

Pointer and Ensell (1975)[270], and Sobagaki et al (1975)[306] normalized data in CIE 1960 or 1976 chromaticity coordinates to provide maps of color appearance. But since we know that these coordinates are not visually uniform, it follows that the maps contained some degree of distortion associated with the nonuniformity of the coordinate system. Normalizing or curve-fitting in a response diagram avoids this kind of distortion.

Unfortunately, it is not possible to avoid distortion completely if results are to be displayed in a chromaticity diagram. In the absence of knowledge about the exact correspondence between points on a chromaticity diagram and points on a response diagram, at least one transform estimate must be made. But the use of response diagrams for curve-fitting eliminates confounding of errors by requiring only one such transform.For example, the D_{65} map can be derived on a CIE 1976 u'v' diagram (such as Figure 13) and the distortion map in response space can be derived for other adaptation conditions . Then additional u'v' diagrams are constructed from relative response distances derived from the response distortion maps. The process is as follows. Consider the point for unitary red at saturation 80 under D_{65} adaptation as shown near the top of the response diagram in Figure 12. The dashed distortion contour for A adaptation shows that the corresponding point (100 red hue, 80 saturation) under A adaptation would be located on the <u>original</u> $\underline{D}_{65}$ map at the same 80 saturation level and a numerical hue value of about 97 (i.e., 88 red/12 blue). Accordingly, the 100 red at 80 saturation point <u>for illuminant A adaptation</u> can be plotted on a CIE diagram <u>at the</u> $\underline{D}_{65}$ <u>map position</u> of 97 hue and 80 saturation. This approach ignores chromaticity altogether for all but the first, D_{65}, map in CIE chromaticity space. This technique has the advantage over making separate transformations to chromaticity coordinates for each adaptation condition, that nonuniformity of chromaticity with respect to response enters the calculations only once; when the original chromaticity map is determined.

The technique described was, in fact, used to generate maps for color appearance under each of the three adaptation conditions for display in CIE 1976 u'v' coordinates. Those maps are shown in Figures 13, 14, and 15. Only the D_{65} map was derived in u'v' coordinates. It was constructed by interpolating among the stimulus chromaticity points of Figure 4; showing sample chromaticities with respect to Illuminant E. Interpolation was in terms of response values and was carried out for every adjoining set of triads. The resultant estimates were used to construct visually a series of contours representing isoresponses in the chromaticity coordinate system. Again, experience and common sense imposed certain restraints on the shapes of the contours drawn; e.g., star-shapes, abrupt changes in second derivative, and generally 'wobbly' contours were avoided in favor of smooth contours. The D_{65} condition was chosen for this transform because the bulk of ulterior information on color appearance exists for that adaptation condition. In this way, a means was provided for checking validity of the original transform. That is, the D_{65} contours constructed in this manner may be compared with Munsell and other data to test the validity of the transform process. Contours for D_{44} and A adaptation were then constructed in u',v' coordinates by utilizing relative distances on the D_{65} contour map as implied by the distortion surfaces of response diagrams such as that shown in Figure 12.

The diagrams of Figures 13, 14, and 15 provide isohue and isosaturation contours of u',v' chromaticity for adaptation to D_{65}, D_{44}, and A illuminants, respectively. Adaptation shifts, such as those conventionally resulting from haploscopic data, may be obtained from the isocolor contours by simply connecting corresponding response points. An example is shown in Figure 16 for the shift from D_{65} to A adaptation. Under A adaptation, the chromaticities denoted by the arrow-heads will have the same hues and saturations as would be elicited under D_{65} adaptation by stimuli having the chromaticities indicated by the arrow-tails. Thus, the

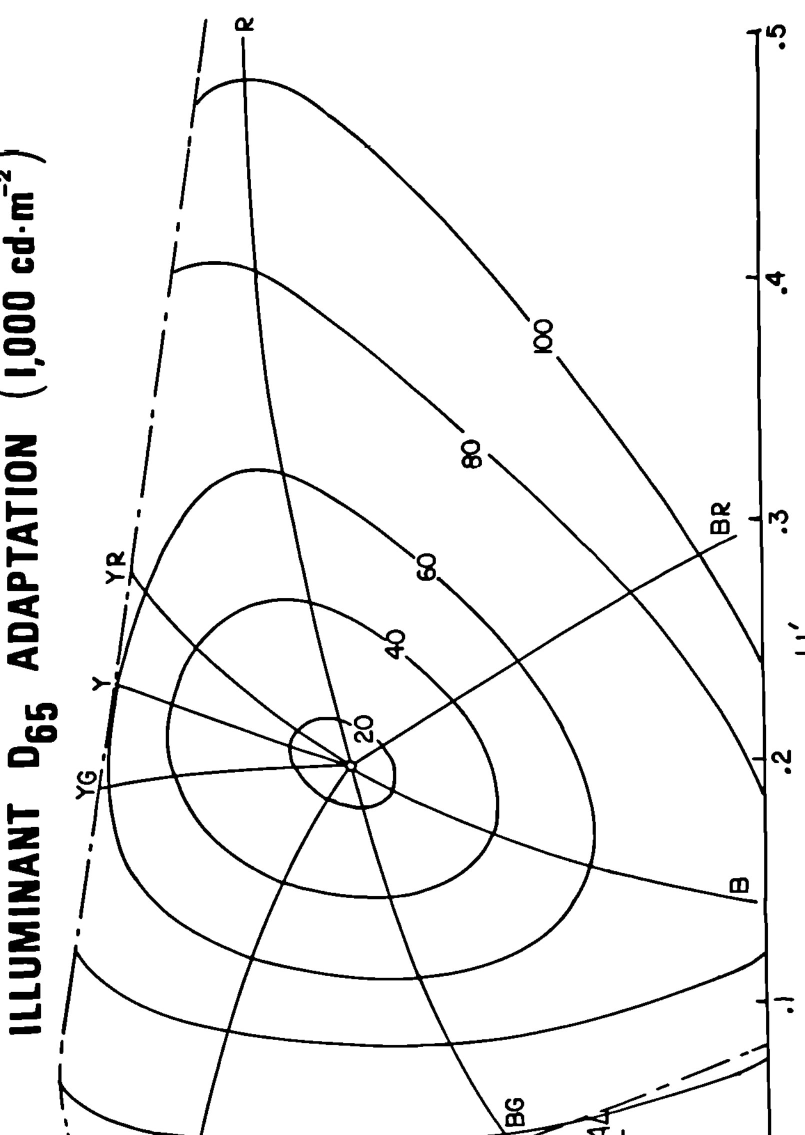
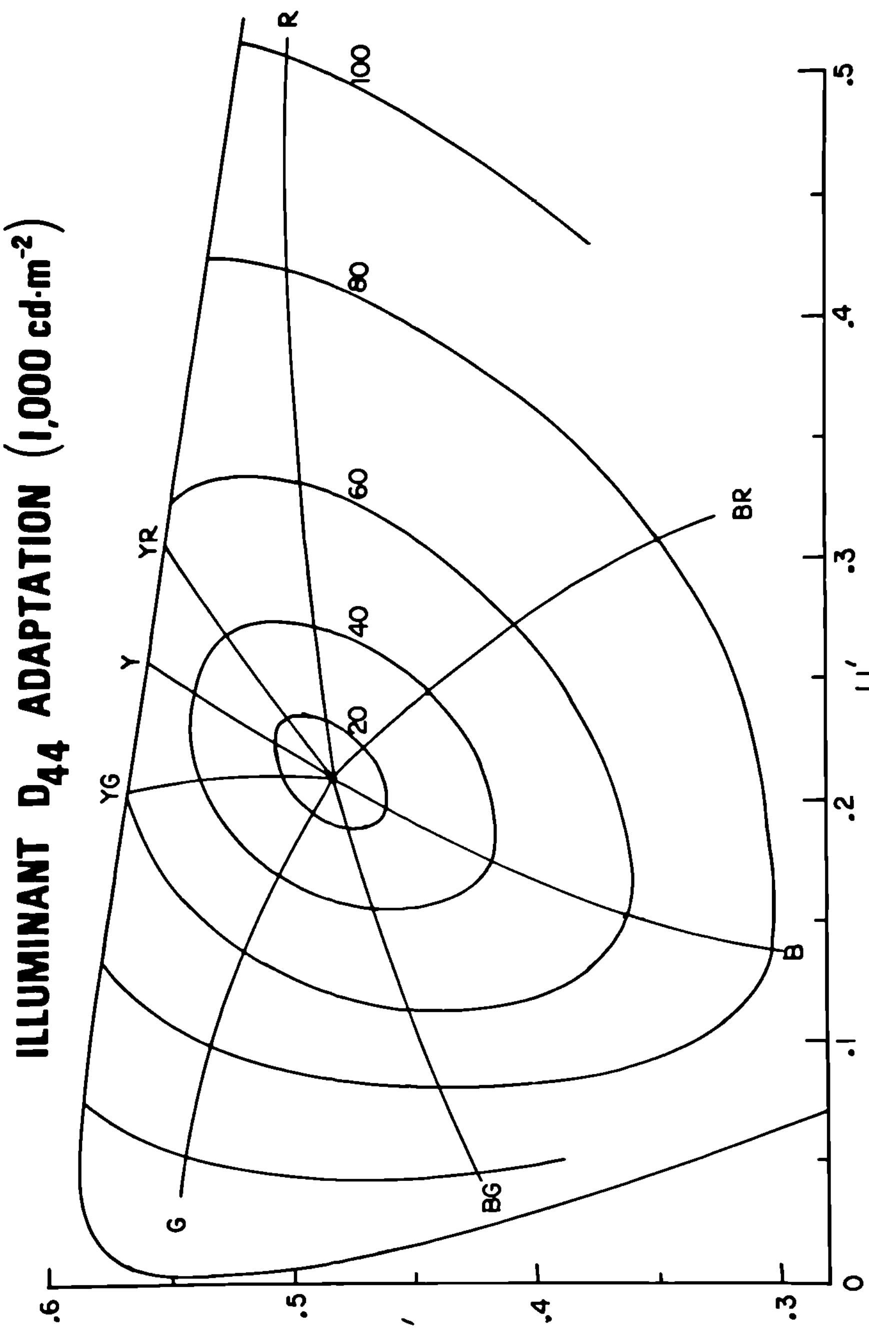

ILLUMINANT D_{65} ADAPTATION ($1,000\ cd \cdot m^{-2}$)
G
BG
B
BR
R
YR
Y
YG
20
40
60
80
100
β=0.2
OPTIMAL
LIMIT
v'
u'
.3
.4
.5
.6
0
.1
.2
.3
.4
.5

Figure 13


ILLUMINANT D_{44} ADAPTATION $(1{,}000\ cd\cdot m^{-2})$
u'
v'
0
.1
.2
.3
.4
.5
.6
R
YR
Y
YG
G
BG
B
BR
20
40
60
80
100

igure 14

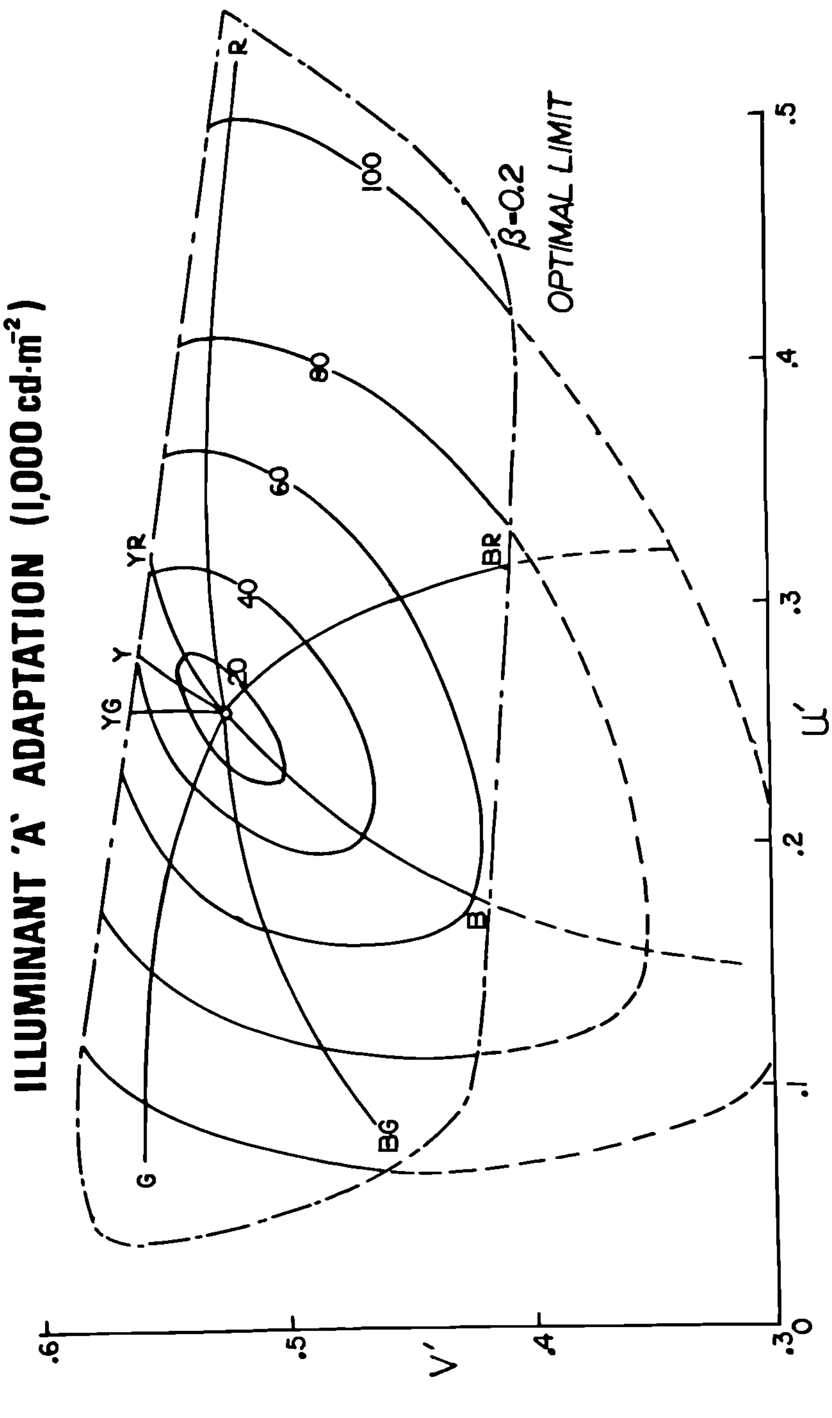

ILLUMINANT 'A' ADAPTATION (1,000 cd·m⁻²)
β-0.2
OPTIMAL LIMIT
R
YR
Y
YG
G
BG
B
BR
20
40
60
80
100
V'
U'
.6
.5
.4
.30
.1
.2
.3
.4
.5

Figure 15

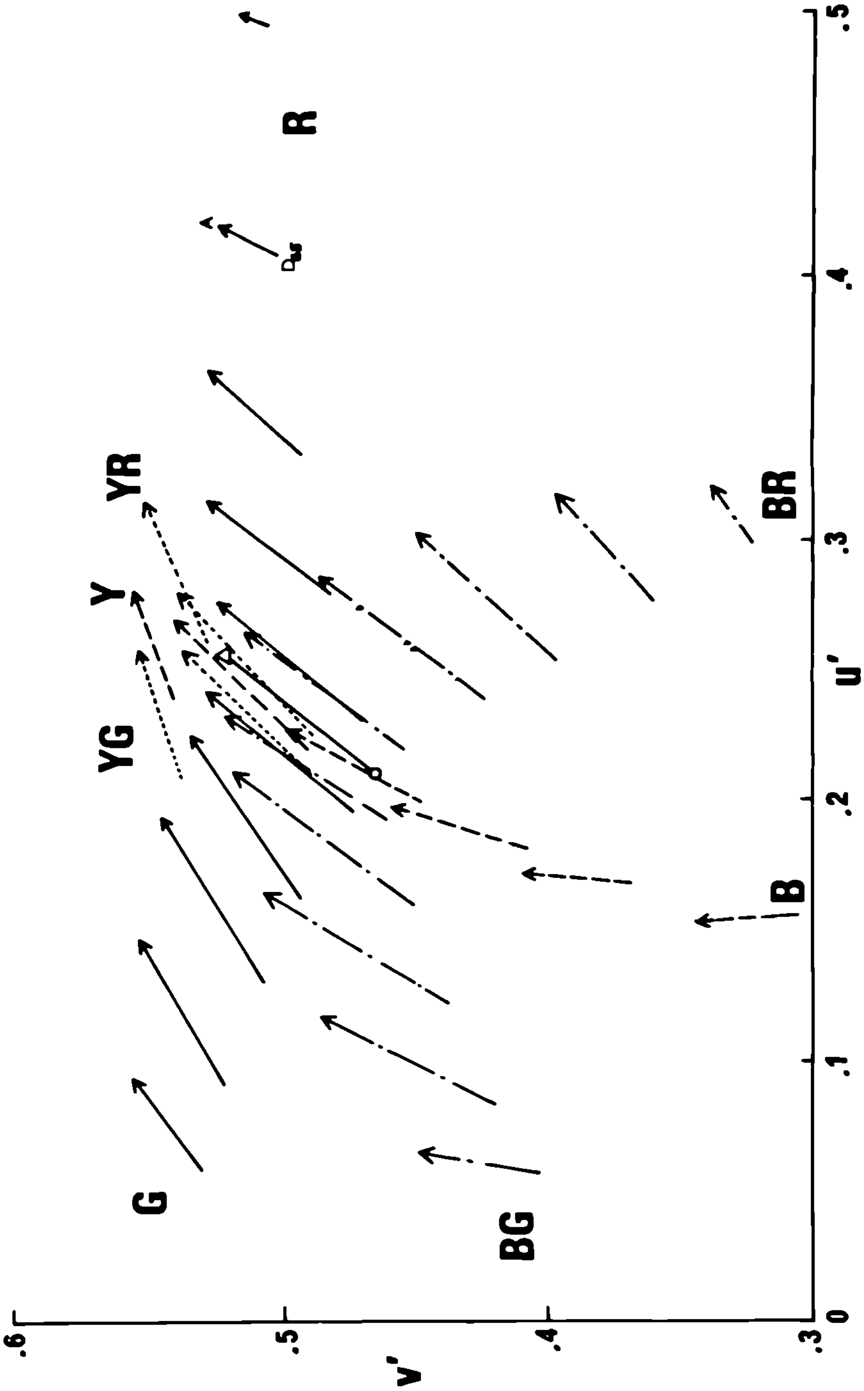


Figure 16

diagrams predict both color appearance relationships as different chromaticities for different adaptation conditions, and corresponding chromaticities (i.e., adaptational metamers) that evoke the same color appearances for different states of adaptation. The experimental results displayed in this way are then versatile and offer a potentially powerful tool for examining several aspects of the influence of chromatic adaptation on color appearance.

However, it is important that their validity be established with some care to ensure that the many inferences which may be drawn do not tower above an unsteady foundation. Therefore, in the following paragraphs, the results of experiments 1, 2, and 3 will be set forth as various combinations of the basic data of Appendix G with particular attention to tests of validity. Results for saturation will be examined first. Then the influence of color temperature on hue will be considered. Both internal and external consistency are important and both will be examined.

Internal consistency of saturation scalings may be examined in a number of ways. We have already seen that observers were consistent in the production of psychophysical scales for saturation over different conditions of adaptation. Another test of internal consistency involves comparisons of magnitude production data with those of estimation scalings. All observers performed some magnitude productions of hue and saturation. In addition, four observers (A, B, C and E) carried out more extensive magnitude productions. In these extended investigations, a total of seven dominant wavelengths were used for scaling saturation by magnitude production for the D_{65} condition at a luminance factor of 0.20 against a 1,000 $cd{\cdot}m^{-2}$ surround. The observers adjusted colorimetric purity to match saturation magnitudes at each of the seven dominant wavelengths. Their individual data were normalized to form a saturation scale common to all observers. This was done by averaging logarithms of colorimetric purity for each magnitude of saturation. In

(Eq. 13)
this way, a psychophysical function was obtained. That function could be used to compute saturation magnitudes for colorimetric purity as well as the inverse. Rational values of purity could then be converted into both saturation magnitude and u'v' chromaticities so that dominant wavelength lines of chromaticity for specified colorimetric purity could be constructed in a CIE 1976 u'v' diagram.

The results are shown in Figure 17. The data circles represent chromaticities that were found to correspond to saturation levels 20, 40, 60, 80, and 100 along the dominant wavelength lines shown as solid lines radiating from the D_{65} illuminant chromaticity. The dashed curves are the saturation contours determined by magnitude estimation for the same stimulus conditions. These estimation contours are the same as in Figure 13 on page 130. They are included for comparison. The agreement between estimation and production of saturation is generally excellent. One data point, at a saturation of 80, is located at some distance from the estimation contour. This point is in an area of the chromaticity diagram where confidence of the estimation data is probably lowest because the distribution of stimuli was most sparse. It may well be that the magnitude production result is the more accurate of the two. In any event, all other points show a high degree of concordance with the estimation loci for saturation. It is, therefore, reasonable to conclude that internal consistency is satisfactorily high in the sense that the same answer obtains with two different experimental approaches to the same question.

The matter of external consistency must be examined by comparing these results with ulterior information on color spacing. Of the available data, those for the Munsell Renotation (Newhall et al 1943)[255] are probably the most widely accepted for reference purposes. Over three million observations went into determination of the Munsell Renotation data. Although the resultant scales should be of the interval variety (because successive interval scaling was used for hue and sat-

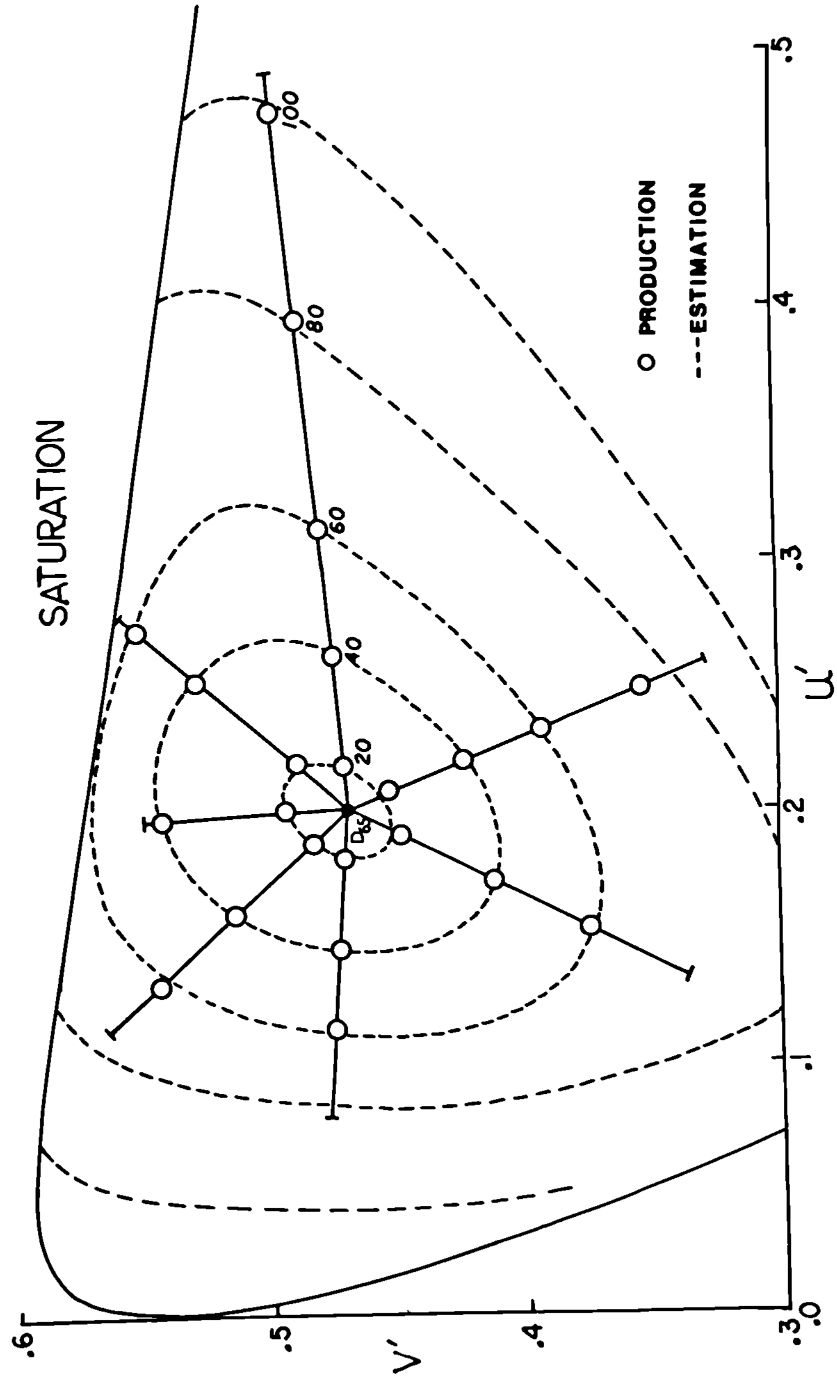

SATURATION
O PRODUCTION
---ESTIMATION
20
40
60
80
100
D65
u'
v'
.0
.1
.2
.3
.4
.5
.6

Figure 17

uration, or Chroma in Munsell notation), we have seen that interval and magnitude scales are often related through a power transform. Therefore, one would expect to find a correlation between magnitude data for saturation and Munsell Chroma. That correlation should assume the form of a linear relation between logarithms of saturation ratios and Chroma; the slope of which corresponds to the exponent of the arithmetic relationship. It is of some interest, then, to compare the saturation contours found here with appropriate contours of Munsell Chroma.

There is one problem to be resolved before a direct comparison can be made. That is a problem which, ironically, could be solved in a straightforward way if a reliable method of chromatic adaptation transformation were at hand. Data collected in experiment 1 here relate to an adaptation illuminant having the chromaticity of CIE Illuminant D_{65}. But the Munsell Renotation data are specified for CIE Illuminant C. Before making a comparison it is necessary to convert one or the other set of results to a common illuminant. Fortunately, the severity of the problem is not great since the chromaticity difference between CIE Illuminants C and D_{65} is not large. In fact, the actual experimental practice during the Munsell Renotation studies usually involved the use of a phase of natural daylight having a correlated color temperature close to that of CIE Illuminant C or what is now CIE Illuminant D_{65} (private communication, S.M. Newhall, May 1953). Presumably, validity of the Munsell spacing would not be seriously violated by a simple transform to the CIE Illuminant D_{65} reference. Choice of D_{65} as a common reference illuminant seems reasonable because it is now the primary daylight illuminant recommended by the CIE; use of Illuminant C is no longer encouraged.

Two forms of simple transformation are immediately obvious: (1) a von Kries transform,[2/5] and (2) a linear translation in CIE 1976 u',v' coordinates. The latter alternative is justified on the basis that the u',v' chromaticity diagram was derived from the CIE 1931 diagram in such a way as to simulate uniformity of threshold color differences (MacAdam 1937)[227] and is a reasonable compromise representation of Munsell spacing (e.g., Wyszecki 1954b; Sugiyama and Fukuda 1960)[369,323]. It probably represents a spacing which is adequate for simulating the conditions of routine industrial inspection (Judd and Wyszecki 1975, pp.295-313)[190]. Therefore, both transforms were examined.

Selected points in the Munsell Renotation array were transformed from Illuminant C adaptation to that for Illuminant D_{65} by a von Kries equation (Eqs 4 & 5) in Judd's (1940)[186] primaries. Also, a grid of the Munsell array in CIE 1976 u',v' chromaticity coordinates was linearly translated to make the neutral points coincide. The results of these two modifications are shown in Figure 18. The u',v' translation is indicated as solid contours. The von Kries transform is shown as the dashed contours. The two are generally quite similar. The flattening of Chroma contours in the region of Hue 5Y exhibited by the von Kries data is characteristic of that kind of linear transformation. As the spectrum locus is approached, the contours tend to be compressed since data in those regions are characterized by diminishing ratios limited at zero. The u',v' translation is not restrained in this manner. It implies that certain high-Chroma samples simply cannot be produced under some adaptation conditions. That accords more realistically with empirical observations than does the von Kries-type implication. For that reason, and because the u',v' translation is so simple, the translation method has been adopted here to effect the small changes necessary to provide a satisfactory simulation of Munsell Renotation spacing in CIE 1976 u',v' coordinates.

Having made this translation, it is now possible to compare the saturation results obtained here with Munsell Chroma contours. This is done in Figure 19. The broken contours are for Munsell Chroma. The solid contours are those determined by magnitude estimation in this work. In addition, solid triangular points are

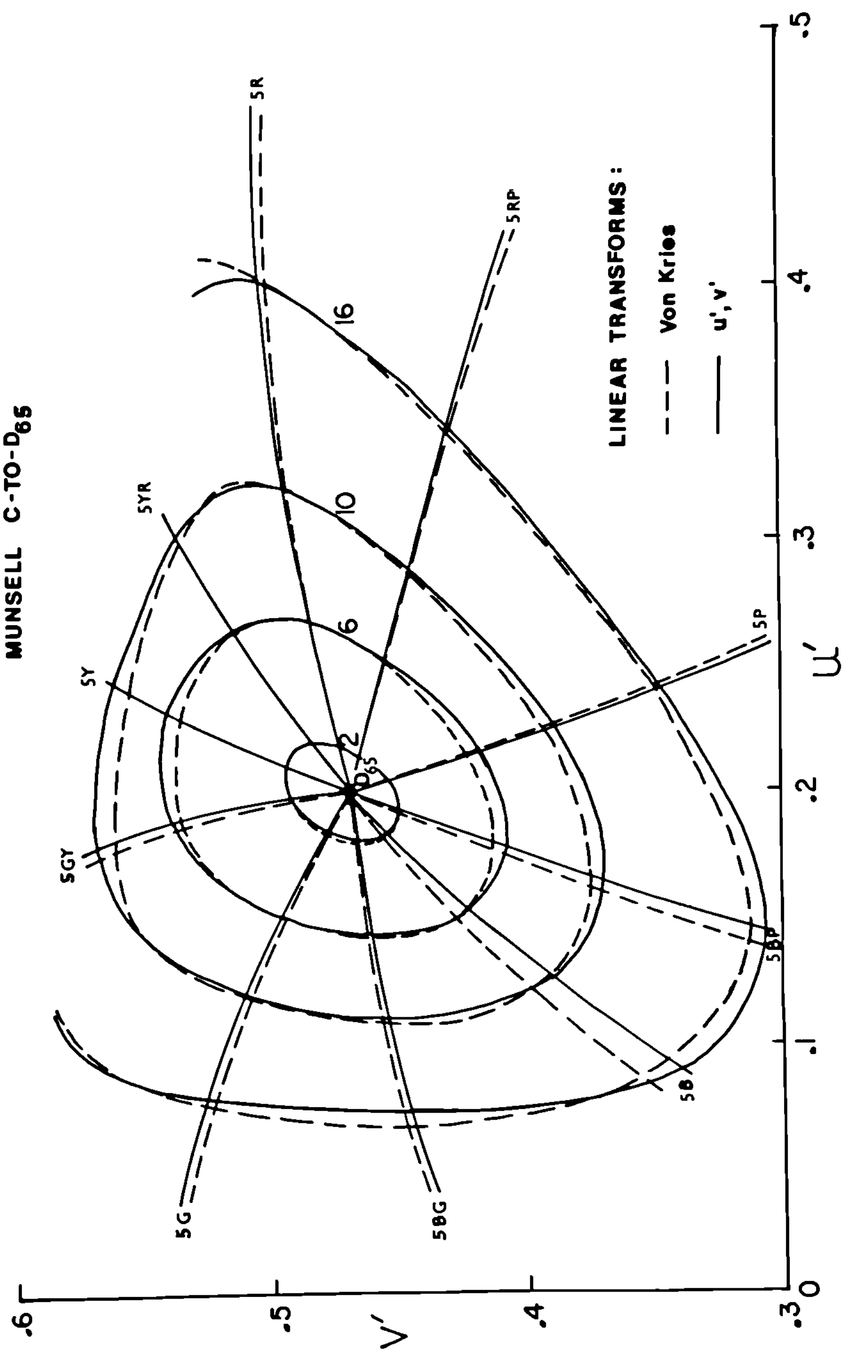

MUNSELL C-TO-D_{65}
LINEAR TRANSFORMS:
Von Kries
u',v'
5R
5RP
5YR
5Y
5GY
5G
5BG
5B
5BP
5P
2
6
10
16
D_{65}
u'
v'
0
.1
.2
.3
.4
.5
.3
.4
.5
.6

Figure 18

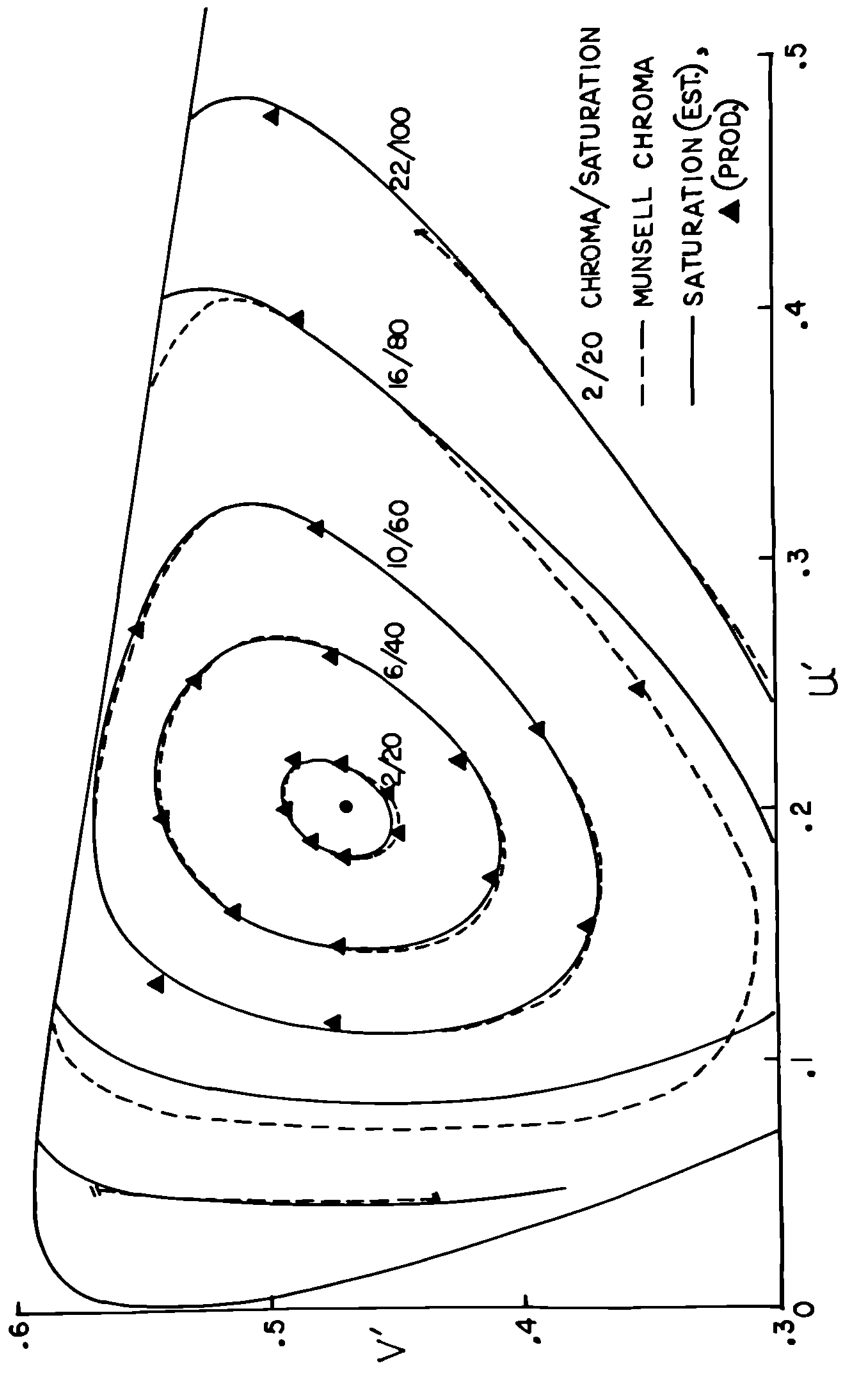

2/20 CHROMA/SATURATION
MUNSELL CHROMA
SATURATION (EST.),
(PROD)
22/100
16/80
10/60
6/40
2/20
U'
V'
.2
.3
.4
.5
.6
.1
0

Figure 1

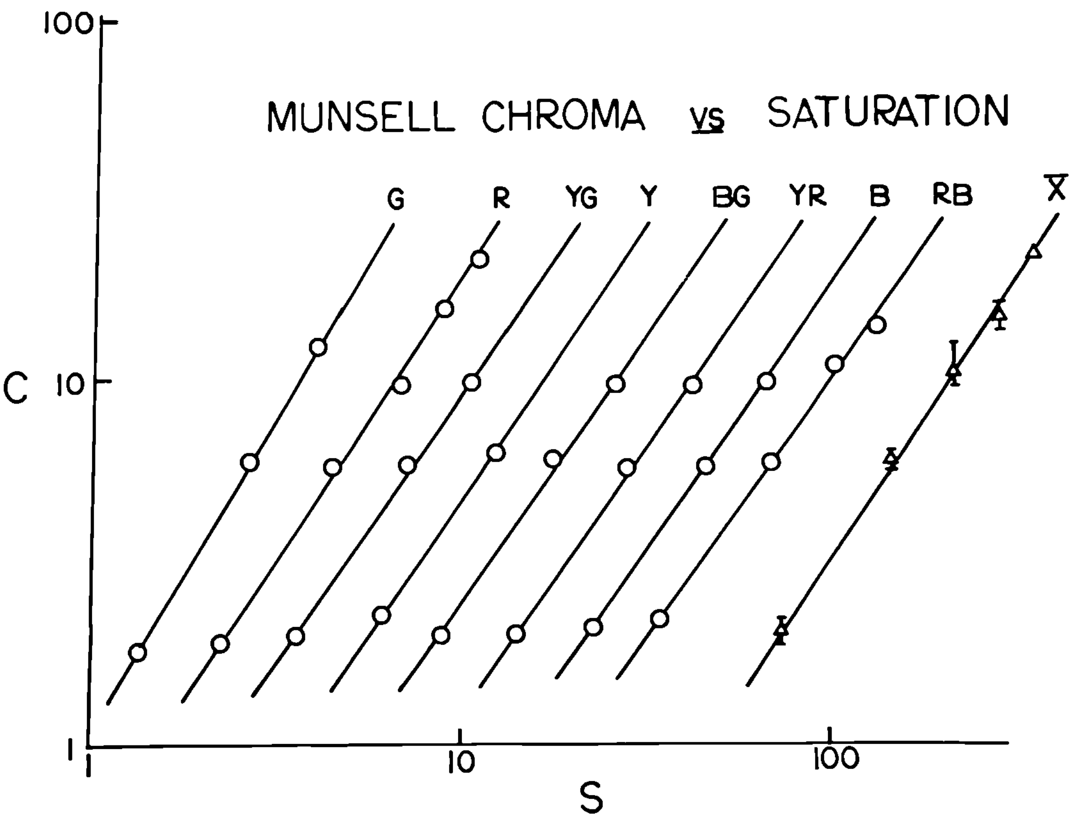

MUNSELL CHROMA vs SATURATION
G
R
YG
Y
BG
YR
B
RB
$\bar{X}$
C
100
10
1
1
10
100
S

Figure 20

included to show the magnitude production results. The similarity of contours is quite satisfactory. Note, however, that there is not a linear relation between Chroma and saturation. A Chroma of 6 corresponds closely to a saturation of 40, Chroma 16 corresponds to saturation 80, and Chroma 22 is close to saturation 100. However, the shapes of the two sets of contours are very similar. Except for the saturation 80 contour, there is almost perfect coincidence throughout the diagram. In that exceptional case, the magnitude production point does coincide with the Chroma contour even if the estimation data differ. In short, the concordance of scaled saturation with the shapes of Munsell Chroma contours is very good.

The fact that the actual values of Chroma and saturation are not identical is a matter of little consequence. If the two are systematically related, then correlative agreement is complete. This is, in fact, the case as may be seen from Figure 20. That graph shows Munsell Chroma (x10) plotted against scaled saturation. Both abscissa and ordinate are arrayed logarithmically. The several functions are displaced arbitrarily along the abscissa for clarity. Open circles represent points along constant hue loci for the four unitary hues and their four intermediates. In each case the points are well fitted by lines in this double logarithmic graph. Therefore, Chroma is related to scaled saturation as a power function; just the relationship that would be expected if Chroma is an interval scale and saturation is a ratio scale of the intensity of chromaticness. Further, the slopes of the eight lines (i.e., the exponents of the relationships) are all very nearly the same for this D_{65} adaptation condition. Because of this, an average function is also shown to the right of Figure 20. The means are plotted as triangles and the ranges for all eight hues are indicated as vertical lines about the triangles. It may be concluded from this that saturation, as scaled here, is related to Munsell Chroma by the same power function for all hues.

This simple relation, plus the high degree of concordance of saturation contours with Munsell Chroma contours, suggests that the scaled saturation data derived here are valid perceptual divisions of color space to the extent that Munsell Chroma may be taken as a useful representation of visual spacing of the chromaticness of colors.

The results for saturation may also be examined in terms of agreement with other visual scaling results for saturation. This work indicates that saturation is a power function of colorimetric purity. Figure 21 shows saturation versus colorimetric purity for a variety of dominant wavelengths under each of the three color temperature adaptation conditions. The data of Figure 21 were obtained from the maps of Figures 13, 14, and 15. The coordinates of Figure 21 are logarithmically spaced. Straight lines through the data points therefore imply power functions; with exponents equal to the slopes of the straight lines in Figure 21. Exponents of the psychophysical functions represented in that figure vary with dominant wavelength. This finding has been reported before (e.g., Indow and S.S. Stevens 1966; Indow 1974)[170,169]. Values of the saturation exponent tends to follow the size of the saturation threshold and both vary systematically with wavelength.[169] Highest values are found around 580 nm and lowest near 400 nm. Exponents of Munsell Chroma versus colorimetric purity vary in a similar way.[169,170]

Figure 22 has been prepared to illustrate several kinds of experimental phenomena that exhibit a similar wavelength dependence. Variation of power function exponents[169,170] is illustrated in 22a and b. Variation of a similar kind, representing luminance ratios required to normalize the Helmholtz-Kohlrausch effect, is shown in 22c for work by Breneman (1958)[46] and in 22d for experiments summarized by Kaiser and Kinney (1975)[196]. Evans' (1974)[93] zero gray content function of wavelength, shown in 22e, also has a similar shape. All these data scatter closely about the average purity threshold (i.e., first limen from a neutral condition) reported by Hurvich and Jameson (1955)[177] as illustrated in 22f.

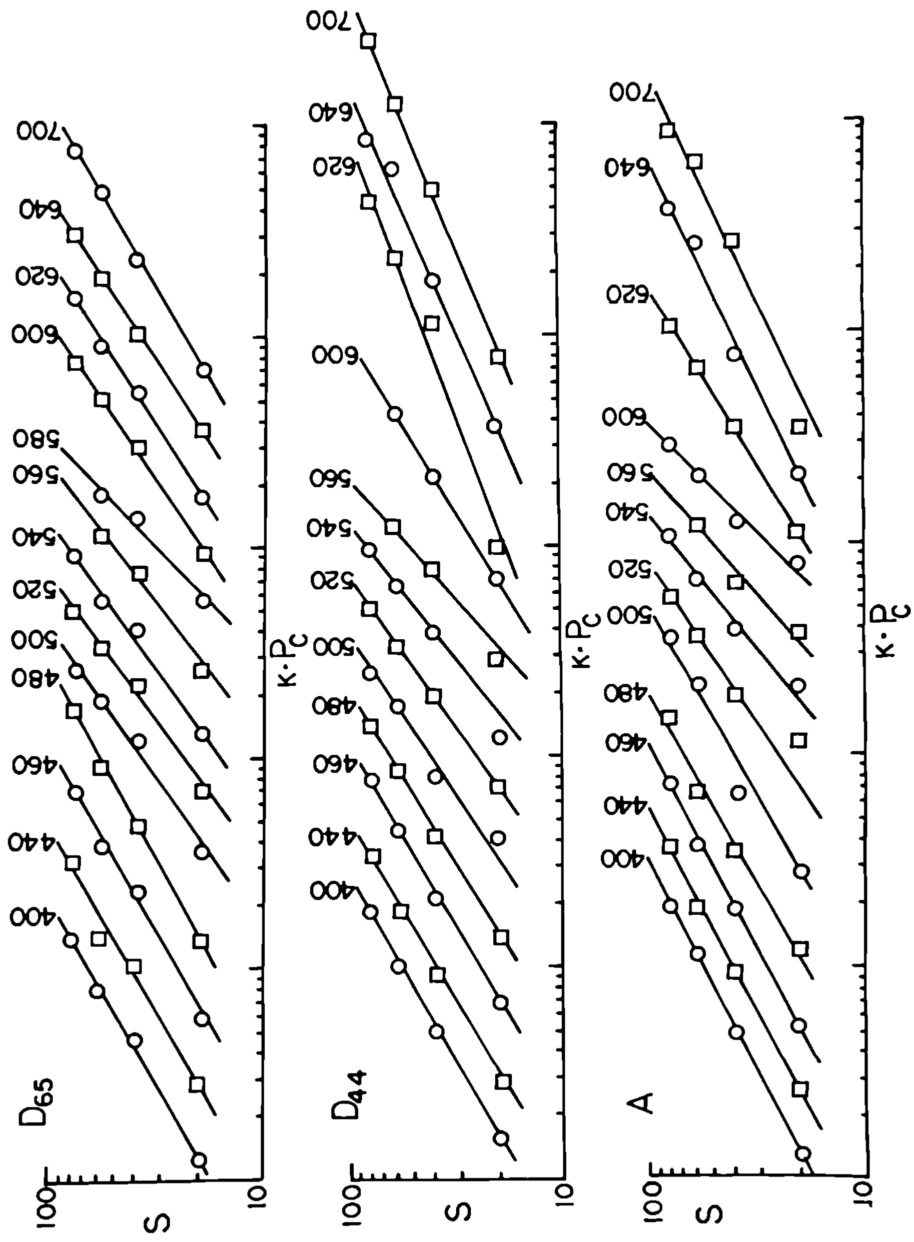
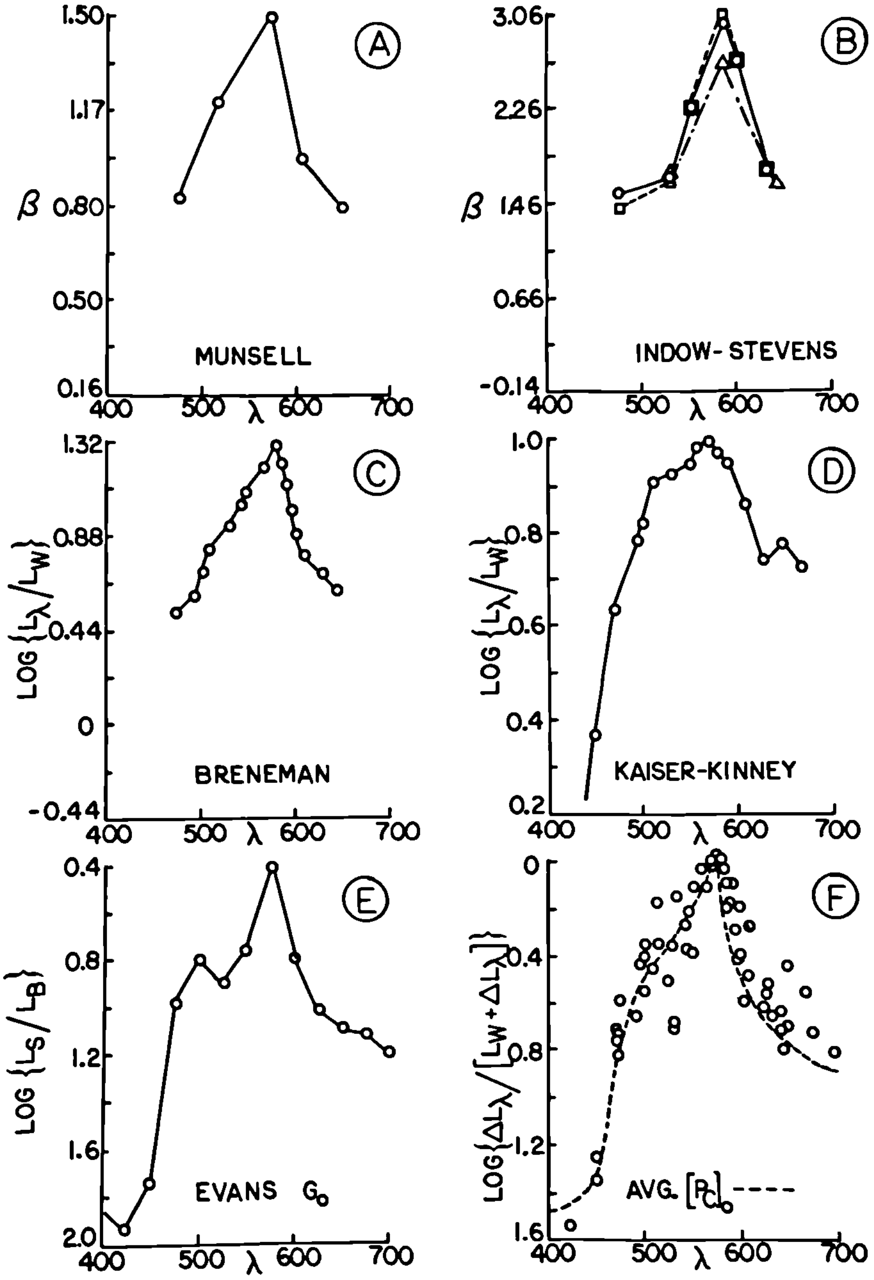

D65
D44
A
S
K·Pc
100
10
400
440
460
480
500
520
540
560
580
600
620
640
700

Figure 21



A
MUNSELL
B
INDOW-STEVENS
C
BRENEMAN
D
KAISER-KINNEY
E
EVANS G₀
F
AVG. [P_C] ----

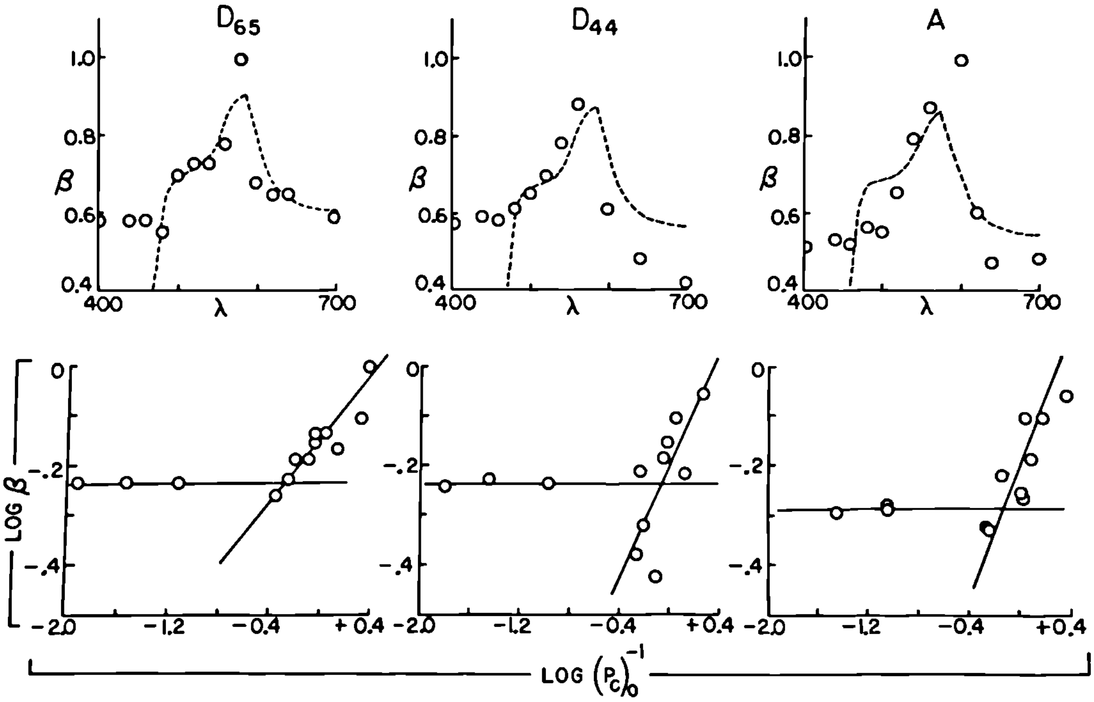
Figure 22

It seems clear that all these phenomena relate to some common basic mechanism of color vision. Saturation appears to depend upon that mechanism.

It is of interest, then, to examine the way in which the exponents of the psychophysical saturation functions determined in this work vary with wavelength. Figure 23 illustrates those relationships for a sampling of dominant wavelengths at each of the three adaptation conditions. The upper graphs show the exponents, β, of of the psychophysical functions plotted against wavelength, λ. The dashed curves are predicted purity thresholds computed from von Kries-type ratios of König (1886)[210] fundamentals for adaptation to D_{65}, D_{44}, and A illuminants. The circular data points relate to those threshold curves about as well as any single set of data shown in the previous Figure 22. Exponents for dominant wavelengths below about 460 nm depart most obviously from the threshold functions.

The relationship of the exponents to purity thresholds is illustrated in a different way in the three lower graphs of Figure 23. Here the logarithms of exponents are plotted against logarithms of the reciprocals of average threshold purities for each of the three illuminant conditions. There are three points in each of these graphs that seem to lie on a horizontal line. These are the three exponents for wavelengths below about 460 nm. The rest of the points lie reasonably well along lines of positive slope. Again, the coordinates are double logarithmic so that the linear relation of positive slope corresponds to a power function. Hence, the saturation exponents for this work are approximately related to purity thresholds through a power transform. Further, the slopes of the lines in the lower graphs are not the same for all three conditions of adaptation. The exponents of psychophysical saturation functions vary with chromatic adaptation. The exponent for the D_{65} condition is lowest among the three conditions, that for A is highest, and the D_{44} case is intermediate.

The saturation data derived in this experiment



igure 23

is wavelength dependent and does correlate with purity thresholds in a manner similar to that found by others for saturation and related phenomena. Further, this research shows that the relationship is generally described by power functions with exponents that vary systematically with color temperature of adaptation. From these facts, and from the concordance of the scaled saturation data with Munsell Chroma, it appears that the present results for saturation have reasonable validity.

Turning now to hue, we may again compare the results for magnitude production with those of magnitude estimation to examine internal consistency. This is done in Figure 24. All observers produced at least eight hues. Extended observations were carried out by four observers (A, B, C and E). Six pairs of filters were used to determine constant hue loci for the unitary hues and their intermediates. Three to five levels of saturation were explored, depending upon hue. The chromaticities of the stimulus end-points are indicated in Figure 24 as small solid circles. The open circles represent average results for hue production. The eight circles lying on lines joining the stimulus end-points are averages for all 7 observers. All other circles are averages for the 4 observers who carried out the extended experiment. In this case, average represents the arithmetic mean of dominant wavelengths of the individual mean settings. Dominant wavelength adjustments were not very different from one observer to another; so the difference between the arithmetic and geometric mean is close to zero. As with magnitude estimation of hue, it was assumed that differences in wavelength settings among observers resulted from inequalities in their physiological capacities for hue perception.

There is generally good agreement between the hue loci for magnitude production and estimation. Perhaps the red and yellow-red productions were biased by the choice of stimulus end-points. But if so, the two hue productions were biased in different ways. Red tends to

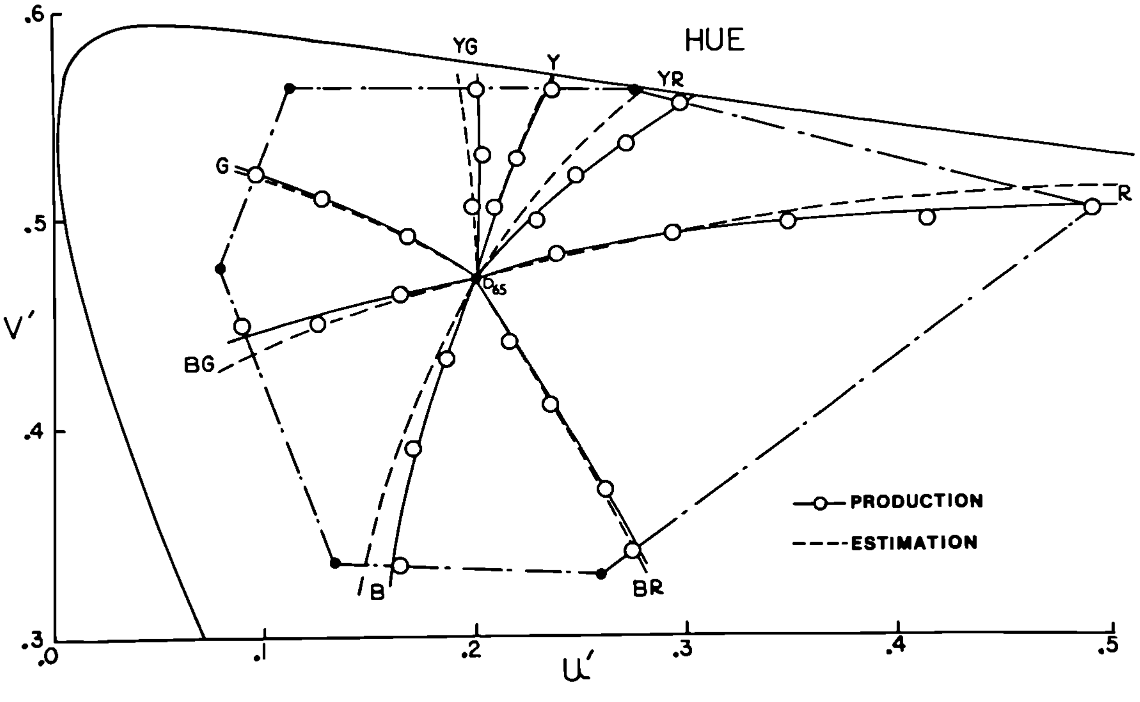
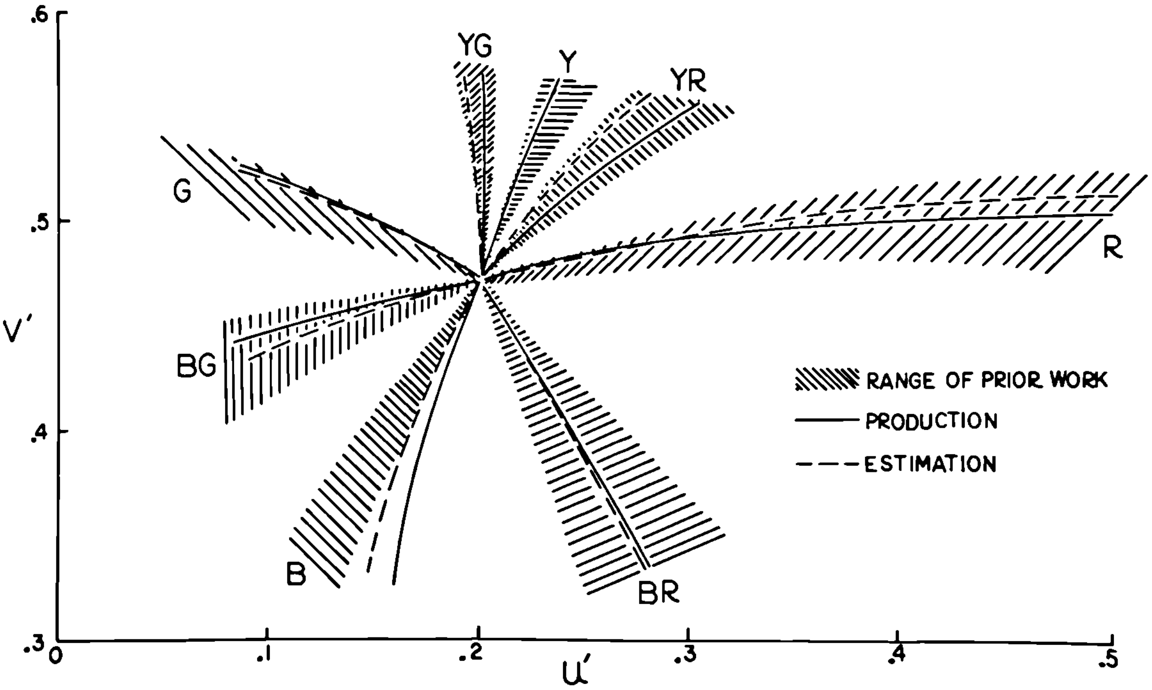

HUE
YG
Y
YR
G
R
BG
B
BR
D_{65}
PRODUCTION
ESTIMATION
.6
.5
.4
.3
.0
.1
.2
.3
.4
.5
V′
u′

Figure 24

be in the direction of the production stimulus end-point compared with the estimation locus for red, but yellow-red production is biased away from the end-point compared with the estimation locus. It seems more likely that the small discrepancies observed in Figure 24 are simply experimental differences arising from ordinary variability. The near coincidence of production and estimation hue loci is enough to justify a conclusion of good internal consistency for hue scaling.

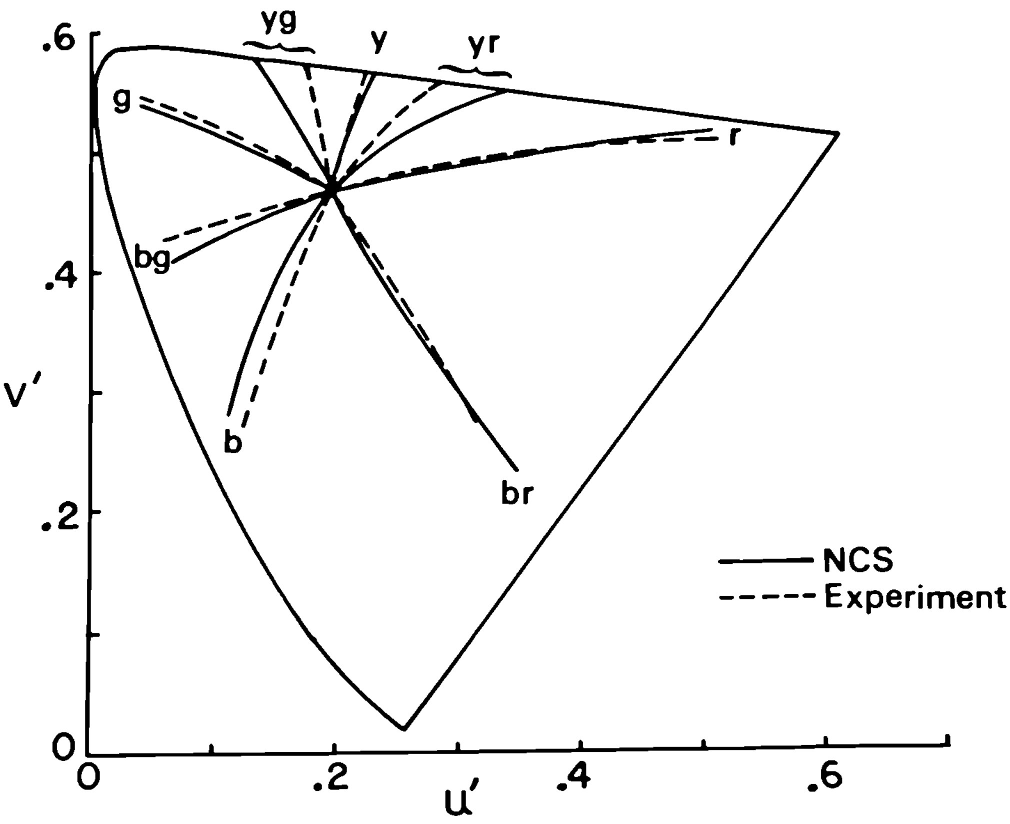
Both production and estimation hue loci are compared with the range of previously reported work in Figure 25. Hue scaling of surface colors has been carried out by a number of workers (Ishak, Bouma and van Bussel 1970; Nayatani et al 1972; Bartleson 1976)[172,252,19]. The ranges represented by these works are indicated in Figure 25 as shaded areas. Loci for magnitude estimations (dashed curves) and magnitude production (solid curves) as determined here are generally located within the shaded areas. The single exception is for unitary blue. In general, however, agreement with ulterior results is satisfactory.

Unfortunately, there is a paucity of other data with which to examine further the external consistency of results for hue. Although many determinations of unitary hues have been reported, they are almost all for the aperture color mode of appearance and usually only at unit purity (e.g., Dimmick and Hubbard 1939a,b; Judd 1951)[79,80,187]. Munsell Renotation Hue contours are of little help because the Munsell notation utilizes five primaries rather than four unitary hues. However, workers in Sweden have recently developed a new spacing of surface colors - a spacing referred to as the 'Natural Colour System' - and Tonnquist (1975)[335] has provided data that may be used to compare the present results for hue with those of the NCS spacing in u'v' coordinates. In the NCS work, hue was scaled in a manner quite similar to that used here. Figure 26 compares the hue loci of the two works. Loci are shown for the unitary hues and their intermediates. Yellow-red and yellow-green magnitude estimation loci from this experiment



.6
.5
.4
.3
V′
0
.1
.2
.3
.4
.5
U′
YG
Y
YR
G
R
BG
B
BR
RANGE OF PRIOR WORK
PRODUCTION
ESTIMATION

Figure 25



igure 26

are closer to the chromaticities of unitary yellow than is the case for the NCS loci. Since the previous Figure 25 does not indicate the same discrepancy for yellow-red and yellow-green loci compared with prior scaling results, these differences with NCS are puzzling. However, in other respects, the agreement between the two sets of data is generally excellent. It seems likely from the comparisons in Figures 25 and 26 that the validity of the hue scaling carried out here is also satisfactory.

Indow (1974)[169] has pointed out that psychophysical functions for hue tend to act like prothetic continua and form power functions (v., Indow and S.S. Stevens 1966)[170] when related to proportions of dominant wavelength, Specifically, when the range of dominant wavelengths separating two stimuli to be mixed colorimetrically is normalized to some constant value, say 100, then the ratio of hue responses is proportional to the ratio of stimulus measures. In other words, dominant wavelengths of stimuli may be treated in the same way as colorimetric purity; wavelength proportion is taken as the ratio of one amount (e.g., luminance) of one component of the mixture to the sum of the amounts of both components of the mixture. That method of characterizing wavelength relations is convenient for many experimental situations in much the same way that colorimetric purity is. One need only work with relative amounts of the components in a two-part mixture.

The same relation may be used to evaluate psychophysical functions for saturation and stimulation. Consider scaling of yellowness in a direction away from red at a saturation level of 20. The dominant wavelengths for unitary red and yellow hues at S = 20 are first determined. Their difference comprises an interval of dominant wavlength. That interval is normalized to 100. A sample at S = 20 with a scaled hue of 75Y/25R has some dominant wavlength intermediate between the two unitaries; i.e., it has a normalized dominant wavlength between 0 and 100. That wavelength proportion may be plotted against the scaled hue proportion. The resulting psychophysical function is much easier to evaluate than if either wavelength or frequency of stimulation were used because there are often very small differences between end-points and samples to be evaluated. The normalized wavelength scale stretches these differences and equalizes them for all quadrants of color space.

This method was used to analyze the present results and it was found that the relations are well fitted by simple power functions. Figure 27a illustrates the relations for a saturation level of 60 for each of the four hue quadrants under both D_{65} and A adaptation. There are four functions in each of the quadrants. The two dashed functions relate to the A adaptation condition and the two solid ones are for D_{65} adaptation. Each line is labeled to show the direction of hue scaling. For example, in the R,Y (upper left) graph, the topmost left line is marked Y→R. That means that it corresponds to redness when moving from the yellow direction. Redness from the blue direction is found in the R,B (upper right) graph. Together, these two functions describe the ways in which redness may be scaled. Similar analogies apply to the other combinations of hue and direction.

The graphs of Figure 27a show something very interesting beyond the simple fact that they are power functions. Referring again to the R,Y quadrant, note that for each adaptation condition there is both a redness-from-yellow and a yellowness-from-red function. The slope of the yellowness-from-red line is much higher than that of the redness-from-yellow line. Since the coordinates of the graph are logarithmic, this means that the exponent of the redness-from-yellow function is lower than that for yellowness-from-red. As it happens, the one exponent is close to the reciprocal of the other. And this reciprocity appears to hold for for all quadrants and for both adaptation conditions. The exponents differ with chromatic adaptation, but in all cases directionally complementary functions show reciprocity of exponents.

Figure 27b shows the exponents of the redness and

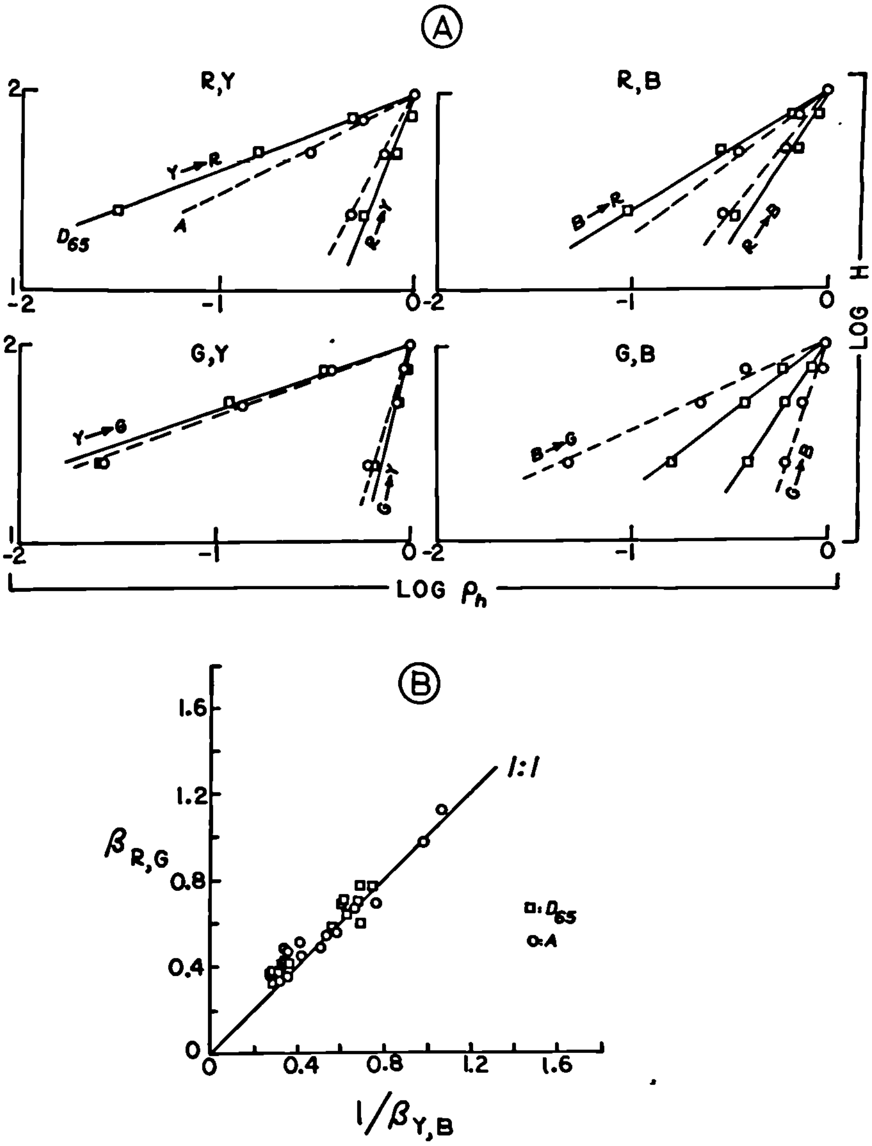

A
R,Y
R,B
G,Y
G,B
Y→R
D65
A
R→Y
B→R
R→B
Y→G
G→Y
B→G
G→B
LOG H
LOG ρ_h
B
1:1
$\beta_{R,G}$
$1/\beta_{Y,B}$
□: D65
○: A

Figure 27

greeness against the reciprocals of the corresponding yellowness and blueness exponents. The circles are for A adaptation and squares are for D_{65}. The points all scatter rather closely about a line of unit slope. Thus, there is a simple and straightforward relation between obverse hue functions: corresponding obverse functions have reciprocal exponents. This serendipitous relation does not appear to have been noted for hue before.

The absolute values of the hue exponents do vary with adaptation, however. In addition, the exponent for a hue psychophysical function depends upon saturation level. Figure 28 illustrates the manner in which hue exponents vary with saturation for D_{65} and A adaptation conditions. The dotted lines included in the D_{65} graph of Figure 28a all have the same absolute slope; either negative or positive. The same symmetry is not evidenced in the A adaptation situation, however.

The foregoing data indicate that hue, as scaled here, does form psychophysical power functions as demonstrated previously by others. In addition, there are clearly some quite simple relations between pairs of hue functions; relations that determine the values of exponents of those power functions. But the power functions do not directly indicate the way dominant wavelength of a constant hue varies with color temperature of illumination; although that information may be derived from the psychophysical functions. To examine these changes, it is necessary to plot hue values directly against dominant wavelength. Figure 29 does this. Dominant wavelengths of the unitary hues and their intermediates, at several levels of saturation, are plotted.

Graphs are presented for D_{65} and A adaptation. In addition, at the bottom of Figure 29, the shift in dominant wavelength from D_{65} to A adaptation is shown. In all three graphs, the uppermost points (labeled 'max') are the wavelengths at which extrapolated hue loci intersect the spectrum locus; or the complementary wavelengths for those that intersect the 'purple boundary'.

Three things are notable from Figure 29. First,

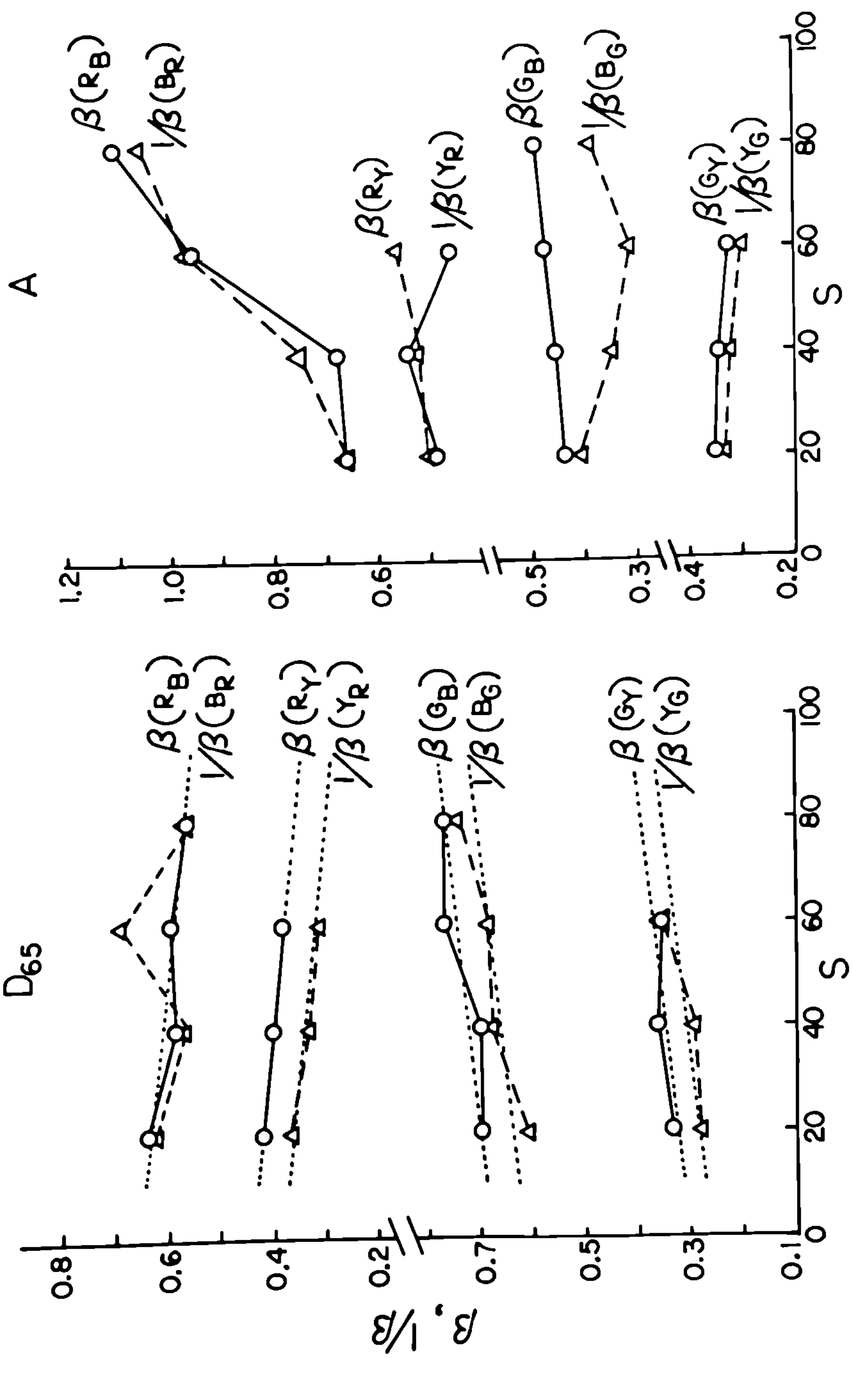


Figure 28

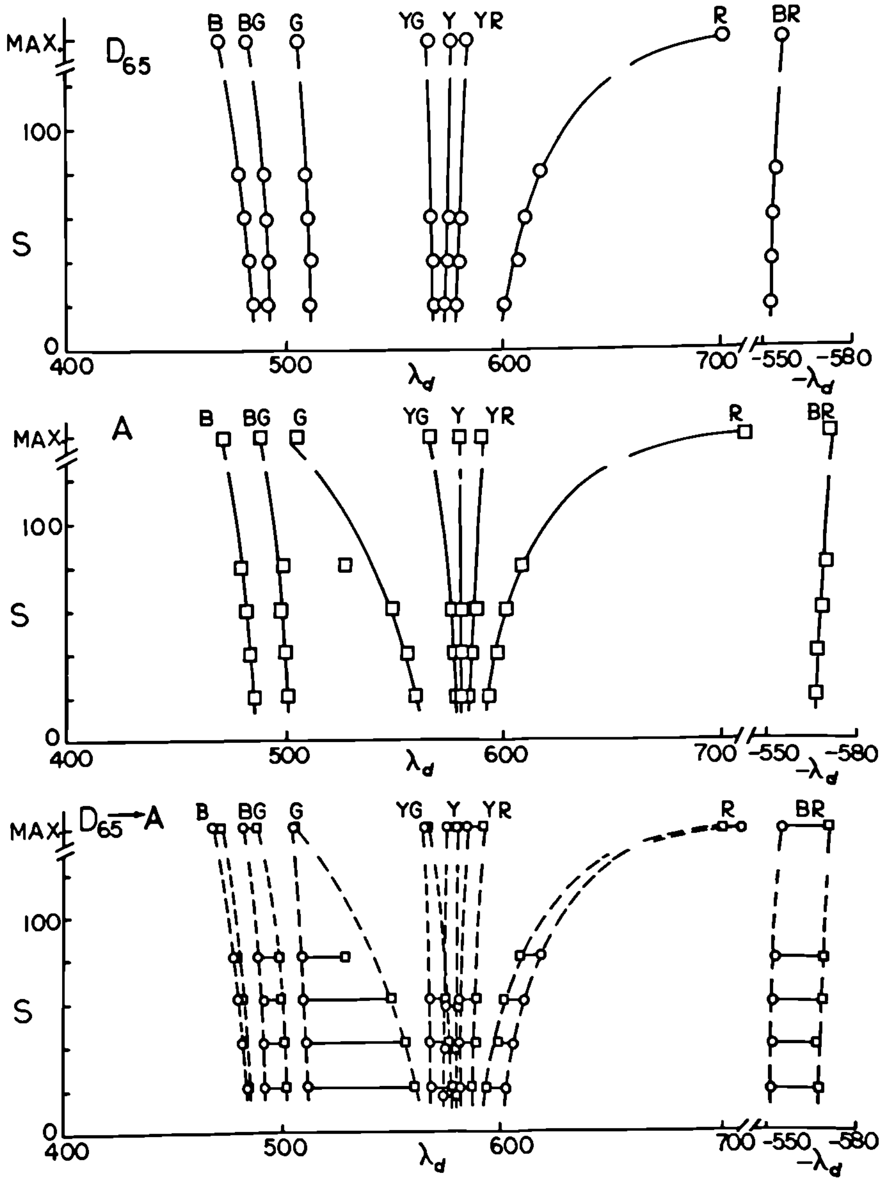
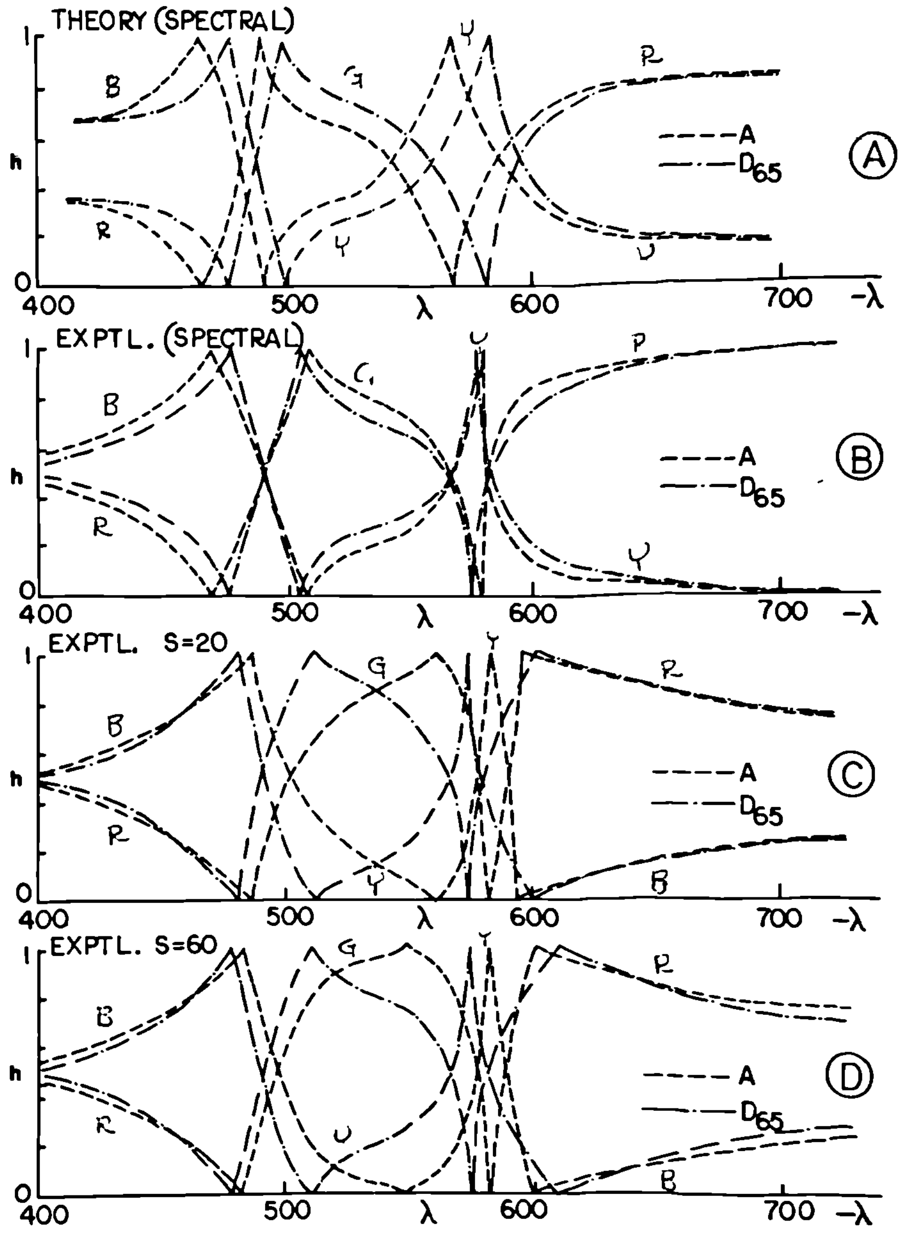

MAX.
D_{65}
100
S
0
400
500
600
700
-550
-580
λ_d
$-\lambda_d$
B BG G YG Y YR R BR
A
$D_{65} \rightarrow A$

Figure 2

the range of dominant wavelengths for hues from blue, through green, to red tends to decrease as saturation decreases. Second, there are distinct shifts in dominant wavelength from one adaptation condition to another. It is interesting that the shift in dominant wavelength from D_{65} to A is different for the various hues depending upon whether their dominant wavelengths are lower or higher than that of unitary yellow hue. Reddish hues tend to shift to lower dominant wavelength with a change in chromatic adaptation to a lower color temperature illuminant. On the other hand, bluish and greenish hues tend to shift to higher dominant wavelengths with the same change in adaptation. The green shift seems to be unique. It may be an artifact or it may be real. Finally, the amount of shift brought about by a change in adaptation depends heavily on saturation level. Greatest shifts in dominant wavelengths are found generally at the lowest saturations. At higher levels the shifts tend to be smaller, and at the 'max' level dominant wavelengths for hues are nearly invariant with adaptation for all but the blue-red (BR) hue.

Figure 29 illustrates what happens to dominant wavelengths of eight hues when chromatic adaptation is changed from D_{65} to A. Figure 30 shows these shifts for all possible hues elicited by stimuli having dominant wavelengths between 400 and 725 nm. In this figure, 'hue coefficients' are plotted against dominant wavelength. Hurvich and Jameson (1955)[164] have proposed a method for computing hue coefficients as ratios of absolute values of opponent chromatic responses. That method was used to compute the hue coefficients for spectral stimuli and they are plotted in Figure 30a. Two sets of hue coefficients are shown: one for D_{65} and one for A adaptation. Both were computed from von Kries-type ratios of König fundamentals. Note that the wavelengths corresponding to unitary blue, green, and yellow (red is not shown since it has a complementary rather than dominant wavelength) are different for the two adaptation conditions. This may be seen by the wavelengths at which hue coefficients are 0 and 1. The shapes of


THEORY (SPECTRAL)
EXPTL. (SPECTRAL)
EXPTL. S=20
EXPTL. S=60
h
λ
400
500
600
700
-λ
A
D_{65}
Ⓐ
Ⓑ
Ⓒ
Ⓓ

igure 30

the theoretical hue coefficient functions in Figure 30a are similar, but they are translated along the wavelength axis with a change in adaptation.

Each hue coefficient function indicates the relative proportions of pairs of unitary hues at every dominant wavelength. This is exactly the kind of raw data obtained for hue in this experiment. The difference, of course, is that experimental determinations involved direct estimates by observers and the theoretical curves are computed from chromatic opponent response functions subsumed from theoretical fundamentals. It is possible, then, to make a direct comparison of experimentally determined hue proportion functions of dominant wavelength with the theoretical hue coefficient curves.

Figure 30b shows hue proportion functions for the experimental data extrapolated to the spectrum locus. The data are simply proportions of unitary hues represented by the maps of Figures 13 and 15. The curves are quite similar in shape to the theoretical spectral functions of Figure 30a. The experimental curves are somewhat compressed in the yellow-appearing region compared with the theoretical functions, but the overall shapes are reasonably close to being the same as those computed from the König fundamentals. This would imply that a large part of the adaptive shift for hue is accounted for by a coefficient rule; as has been suggested by others (Cicerone, Krantz and Larimer 1975)[66].

Figure 30c and d illustrate the shapes of these hue proportion functions for saturation levels of 20 and 60, respectively. It may be seen from these two graphs that dominant wavelengths for unitary hues tend to be more similar (i.e., are compressed along the wavelength scale) at lower saturation levels than for spectral stimuli. In addition, hue coefficients for all wavelengths change with saturation. These variations are not predicted by a simple coefficient rule for adaptation. The observed changes suggest the need for an additive response or induction process such as that proposed by Hurvich and Jameson (1958; Jameson and Hurvich 1972)[165,183]. At the same time, the basic similarity to the spectral theoretical functions implies that opponent induction alone is not sufficient to predict completely the chromatic adaptation changes observed in hue. This inference has been drawn from other kinds of data as well (Wooten 1970; Cicerone, Krantz and Larimer 1975)[359,66].

Thus, the results of this work, when presented as hue coefficient functions, provide rather complete information about hue shifts with chromatic adaptation. The forms of the observed hue-dependencies on color temperature of adaptation are consistent with other works. Similarly, saturation shifts described as wavelength-dependent functions of scale exponents and colorimetric purities provide powerful means for evaluating the effects of chromatic adaptation on absolute saturation. In the case of saturation, as for hue, it appears that both internal and external consistency is quite high for the work reported here. It seems justifiable to assume that the present data reflect primarily color appearance changes induced by adaptation with satisfactorily high validity.

Effect of luminance factor

The effect of luminance factor on color appearance was studied in experiments 4 through 7 of Table VII on page 101. Three observers (A, C and E) performed magnitude estimations on all 24 stimuli at luminance factors of 0.07 and 0.43 for the D_{65} condition in experiments 4 and 6. Those luminance factors correspond closely to Munsell Values 3 and 7. Together with the same observers' data from experiment 1, there were, then, complete scalings for Values 3, 5, and 7. The results are tabulated in Appendix H. Figure 31 shows a response diagram of those results for the average observer. The circles in that figure represent color appearance values at Value 7, squares are for Value 5, and triangles are shown for Value 3.

The general trend of the data is obvious. Satura-

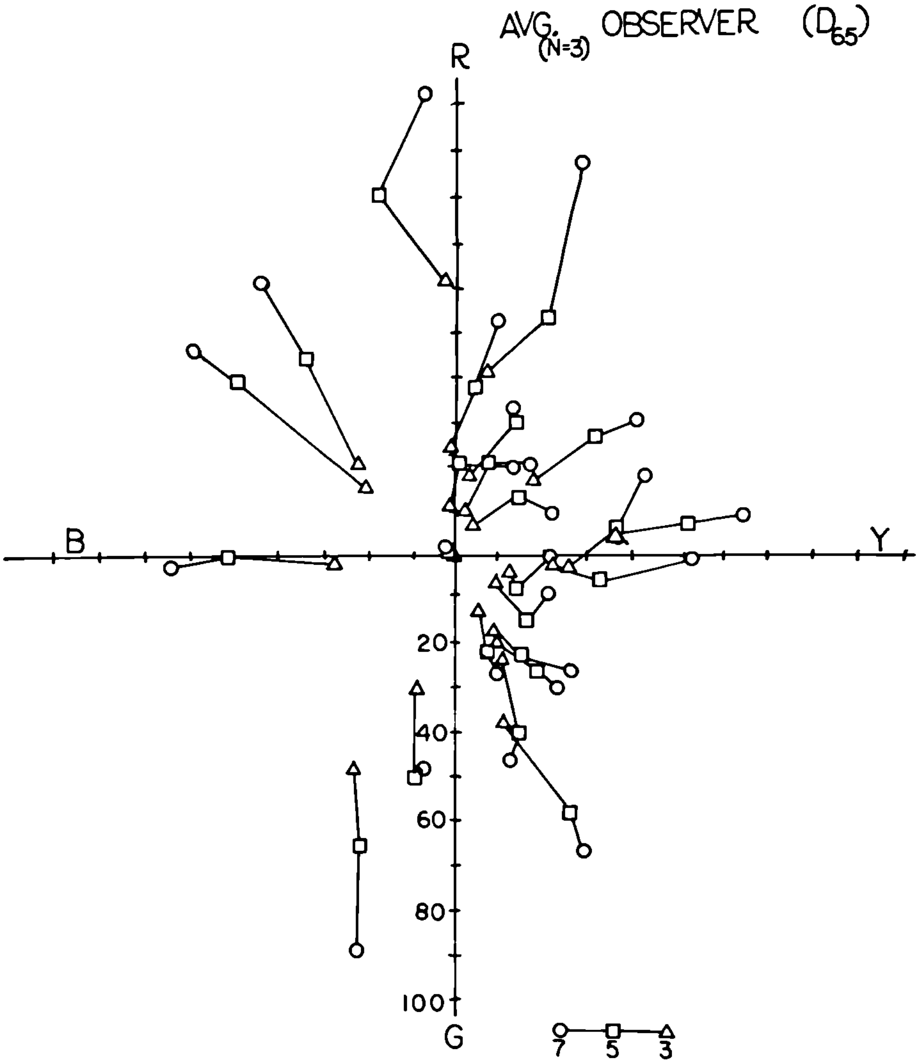
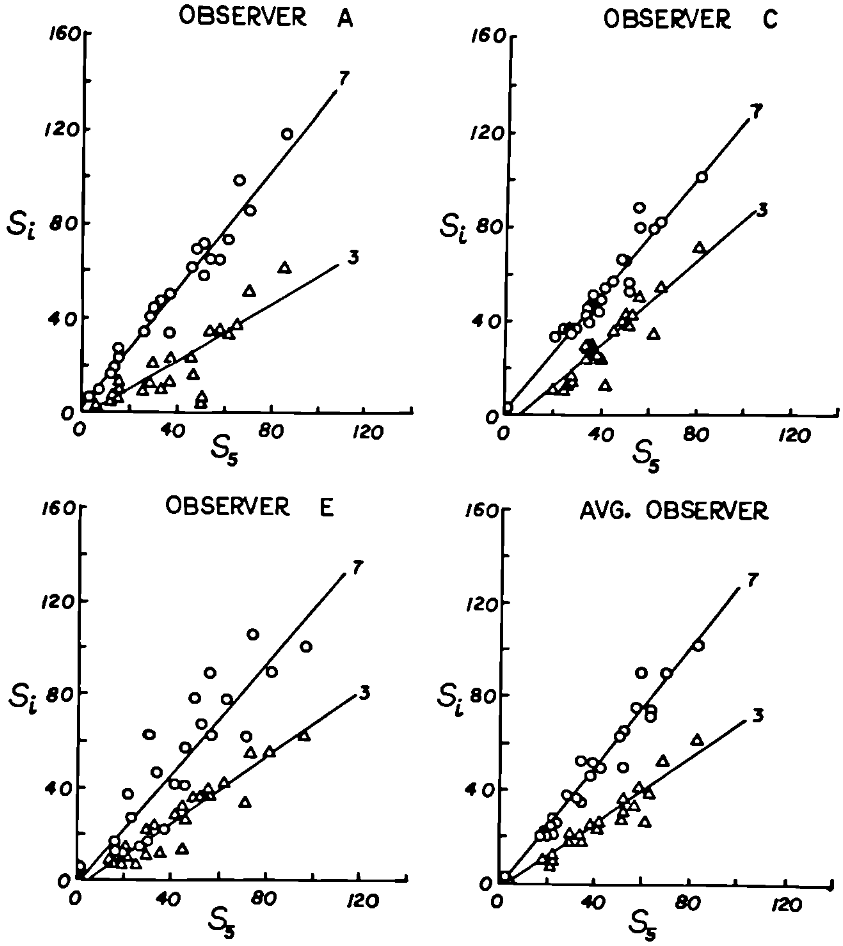


Figure 31



[ILL. D_{65} ; 1,000 $cd \cdot m^{-2}$]

Figure 32

tion of a constant chromaticity stimulus decreases as luminance factor (Munsell Value) decreases. That trend was the same for all three individual observers. Figure 32 illustrates the way in which saturation at Value 3 and 7 related to saturation at Value 5 for each of the observers and their common average observer. In each case, the saturations were linearly related over Value levels. Saturation at Value 7 was higher for all stimuli than at Value 5. Saturation at Value 3 was lower than for Value 5. Table XI lists the linear regression equations, and coefficients of determination, for Value 7 and 3 saturations on the saturation at Value 5 for each of the observers.

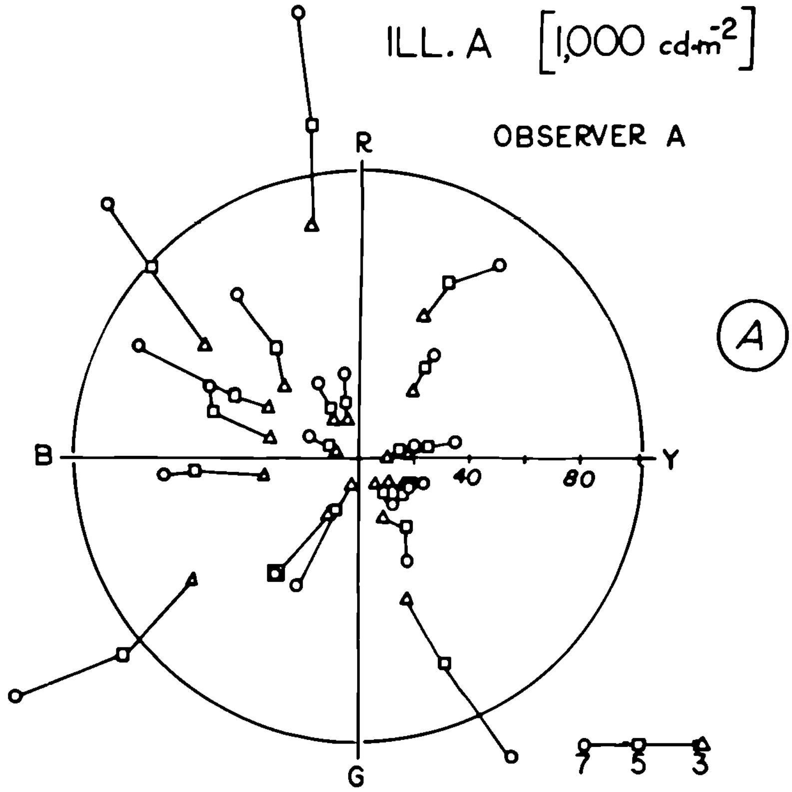
Table XI

D_{65} Saturation - Luminance Factor Effects

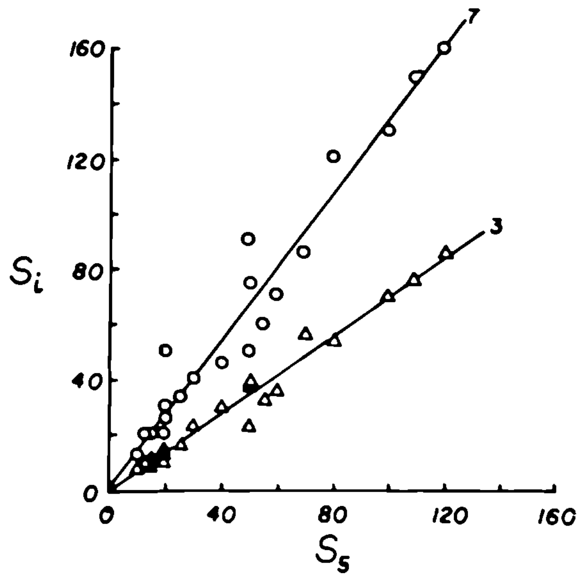
Observer A:	$S_7 = 1.26\ S_5 + 2.21$	$(r^2 = 0.95)$
	$S_3 = 0.61\ S_5 - 3.87$	$(r^2 = 0.70)$
Observer C:	$S_7 = 1.22\ S_5 + 2.57$	$(r^2 = 0.92)$
	$S_3 = 0.87\ S_5 - 5.62$	$(r^2 = 0.87)$
Observer E:	$S_7 = 1.18\ S_5 - 1.92$	$(r^2 = 0.77)$
	$S_3 = 0.71\ S_5 - 4.39$	$(r^2 = 0.88)$
Average Observer:	$S_7 = 1.28\ S_5 - 1.51$	$(r^2 = 0.94)$
	$S_3 = 0.70\ S_5 - 3.22$	$(r^2 = 0.90)$

The data of Table XI indicate that saturation at Value 3 was roughly 30 per cent lower and at Value 7 about 30 per cent higher than at Value 5. There is some slight indication, from the coefficients of determination, that saturation at the lower luminance factor was more difficult to scale than saturation at the higher luminance factor.

Observer A repeated the same experiment for the illuminant A adaptation to determine whether these relationships held for adaptation to lower color temperature as well (experiments 5 and 7 in Table VII). His data are listed in Appendix I. Figure 33a shows



ILL. A [1,000 cd·m⁻²]
OBSERVER A
R
B
Y
G
40
80
7
5
3
A



160
120
80
40
0
S_i
0
40
80
120
160
S_5
7
3
B

igure 33

the resultant response diagram and Figure 33b provides a graph of Value 3 and 7 saturations versus that at Value 5. The regression equations for these illuminant A results are given in Table XII.

- -

Table XII

A Saturation - Luminance Factor Effect

Observer A:

$$S_7 = 1.31\ S_5 + 1.75 \quad (r^2 = 0.95)$$

$$S_3 = 0.69\ S_5 - 0.18 \quad (r^2 = 0.97)$$

- -

Table XII indicates that approximately the same relationship holds for A adaptation as for D_{65}.

Accordingly, a single equation may be written to approximate the change in saturation encountered for Munsell Values different from some reference Value; Value 5, for instance. For convenience, we may call such an equation the 'saturation factor'. It predicts saturation elicited by a stimulus of the same chromaticity as a function of its saturation at Value 5 for any other Munsell Value. Using deviations of ±30% for Values 3 and 7 compared with Value 5, the saturation factor (f_s) turns out to be:

$$f_s = 0.145\ V + 0.255 \qquad (16)$$

where V = Munsell Value.

The corresponding 'Chroma factor' may be deduced from the published Munsell Renotation data (Newhall et al 1943)[255]. That equation is:

$$f_c = 0.150\ V + 0.250 \qquad (17)$$

The experimentally determined saturation factor of Equation 16 is very close to the Munsell Renotation relation of Equation 17. They differ by only 0.005 in both slope and intercept values.

However, Munsell Value is defined by the Munsell Renotation for relative luminance (x100) as a fifth-order polynomial of Value (Newhall et al 1943)[255]. It would be somewhat more convenient to express a saturation factor as a direct function of luminance factor. An expression of this kind can be derived by using a power of luminance factor; for example, the one-third power of luminance factor (x100). Figure 34 illustrates two such functions; one for the experimental results obtained here and one for Munsell Chroma. The equations for those functions are:

$$\text{(experimental result)} \quad S_r = 0.370\ L_r^{\frac{1}{3}} \qquad (18)$$

$$\text{(Munsell Renotation)} \quad C_r = 0.375\ L_r^{\frac{1}{3}} \qquad (19)$$

where S_r stands for saturation relative to that at $L_r = 19.77$; C_r is Munsell Chroma at $L_r = 19.77$; L_r is luminance factor times 100.

The manner in which saturation contours change with luminance factor may be determined by applying Equation 18 to the data of Figures 13, 14, or 15; i.e., the contour maps in u',v' coordinates. Such changes for the D_{65} adaptation at saturation levels 20 and 60 are illustrated in Figure 35. Three Value levels are shown: Munsell Values 3, 5, and 7. The purity corresponding to constant saturation decreases as luminance factor (or Value) increases, for any line of dominant wavelength. Conversely, the saturation of a constant chromaticity stimulus increases with luminance factor. Thus, the maps of Figures 13, 14, and 15 need only be expanded or compressed according to the saturation factor, S_r, in order to determine a new saturation contour for some different luminance factor plane.

The effect of luminance factor on hue was also examined from the data tabulated in Appendix H. The results of that analysis are shown in Figure 36 for each of the 3 observers and their average. Ordinate values indicate the hue shift when changing from high (Value 7) to low (Value 3) luminance factors. The abscissa provides a linear array of the 0 to 100 hue circle. The two upper graphs (labeled 'Bezold-Brucke' and 'Munsell') show the approximate hue shifts over roughly the same range of luminance factor decrement.

The dashed curve labeled 'Bezold-Brucke' represents the experimental data of Purdy (1931)[273]. Those

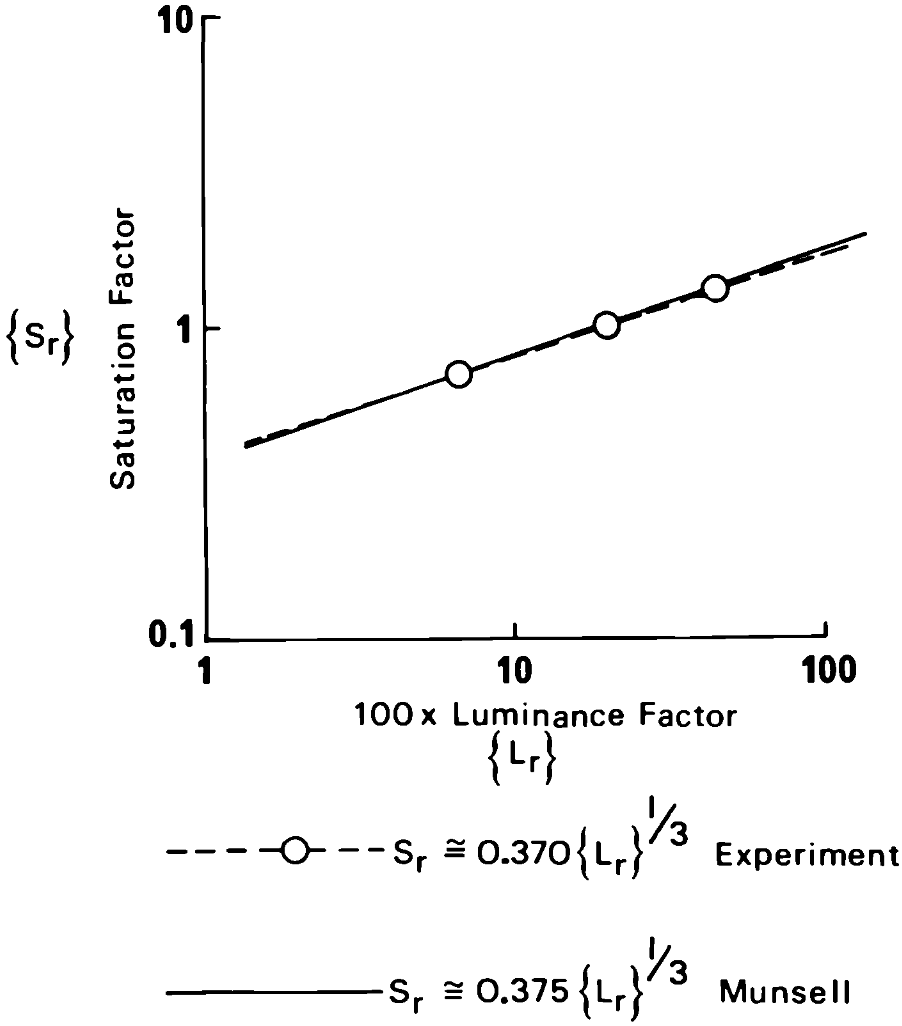
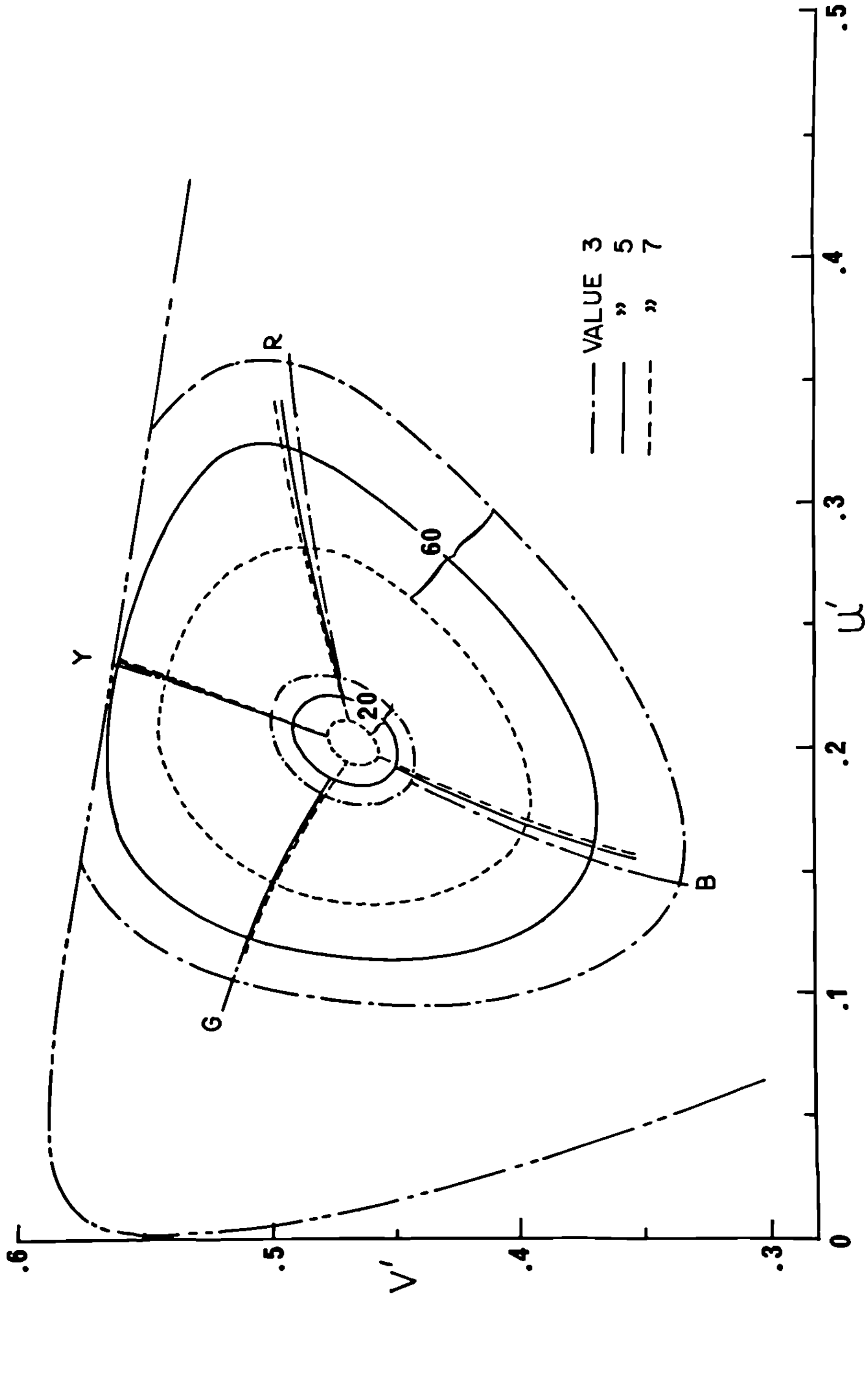
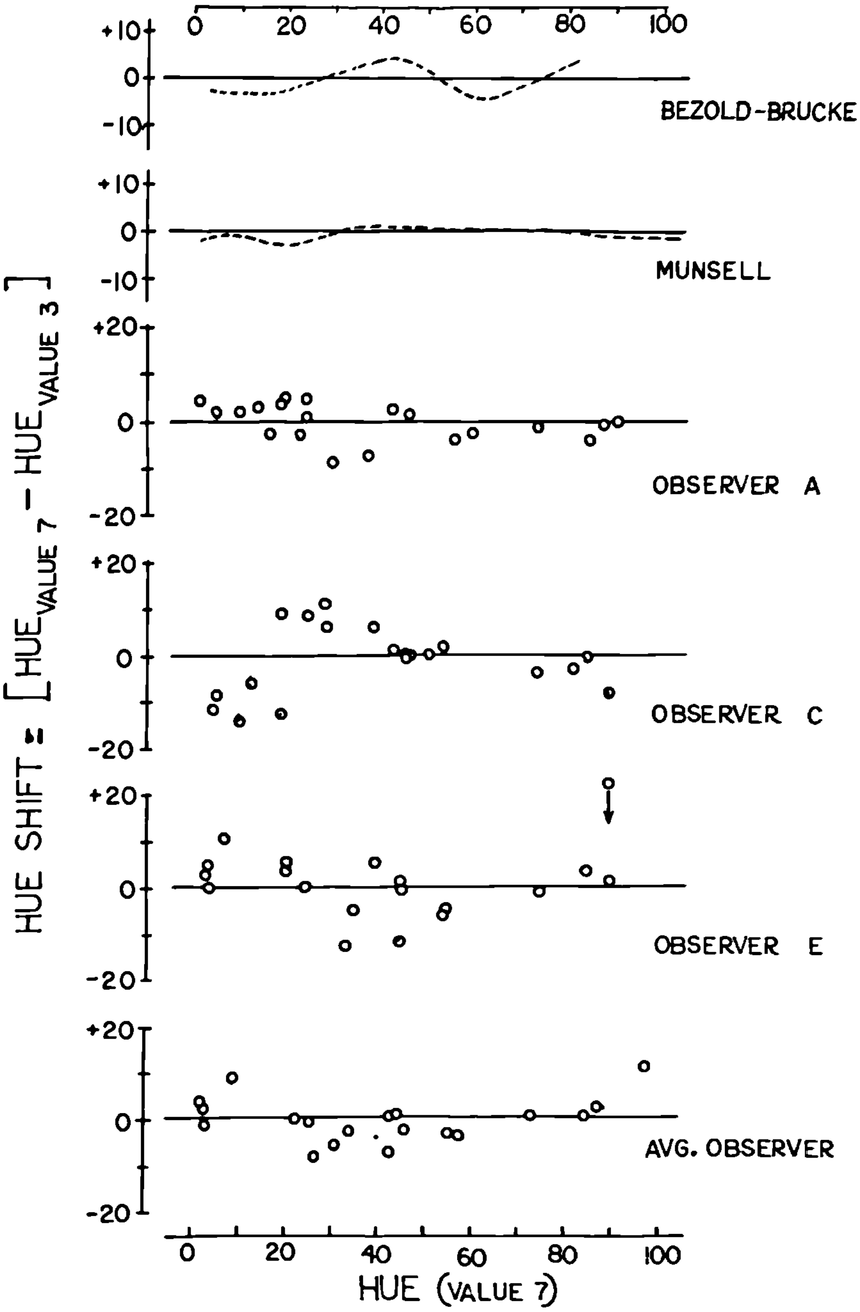

10
1
0.1
Saturation Factor
{Sr}
1
10
100
100 x Luminance Factor
{Lr}
$S_r \cong 0.370\{L_r\}^{1/3}$ Experiment
$S_r \cong 0.375\{L_r\}^{1/3}$ Munsell

Figure 34



igure 35



BEZOLD-BRUCKE
MUNSELL
OBSERVER A
OBSERVER C
OBSERVER E
AVG. OBSERVER
HUE SHIFT = [HUE VALUE 7 − HUE VALUE 3]
HUE (VALUE 7)

igure 3

data have been transformed from differences in dominant wavelength to approximations of scaled hue differences by plotting the data for dominant wavelength of hue coefficients determined by Boynton and Gordon (1965)[42] on a hue circle with unitary yellow at 578 nm (v., Boynton 1975)[39]. Each of Purdy's dominant wavelength differences was then transformed to an approximate hue difference from this wavelength-calibrated hue circle. The resultant function in Figure 36 merely provides a general indication of the shift in perceived hue associated with the Bezold-Brucke phenomenon for a 10:1 decrement in luminance of the focal stimulus.

The dashed curve labeled 'Munsell' indicates the differences in hue associated with Munsell Renotation for a change from Value 7 to Value 3 at a Chroma 6 level (approximately a saturation of 40 in terms of the present study). Again, the shape of the curve is simply for approximate comparisons.

Data points for the 24 stimuli - shown as circles in Figure 36 - scatter about the zero hue shift lines for all the observers. There does not appear to be a systematic shift with hue over the range of luminance factors investigated here. Certainly, there is no trend that is obviously similar to either the Bezold-Brucke shifts or differences in Munsell spacing between the two luminance factor levels examined. Either hue does not shift over this range of luminance factors, or the data collected here are too coarse to measure that shift. Considering the scatter of data points and the small systematic shifts of the comparison functions, the latter inference may well be the correct one. In any event, the shifts in hue are notably smaller than shifts in saturation over the same range of variation in luminance factor.

In summary, then, it was found that changes in luminance factor gave rise to systematic shifts in saturation. Those shifts are very similar to the ones implied by the 1943 Munsell Renotation data. However, if luminance factor has a systematic effect on hue, the experimental results presented here do not indicate it.

Effect of illuminance

Thus far, all experimental phases have involved surrounds of 1,000 $cd \cdot m^{-2}$. The four additional experiments that will now be described, incorporated surrounds and stimuli at lower luminances. Experiments 8 and 9 were conducted with surround luminances of 500 $cd \cdot m^{-2}$ and stimuli at 100 $cd \cdot m^{-2}$. Experiments 10 and 11 used 200 $cd \cdot m^{-2}$ surrounds and stimuli at 40 $cd \cdot m^{-2}$. The two even numbered experiments were with D_{65} adaptation and the odd numbered experiments were with A adaptation.

Results for experiments 8 and 9 are listed in Appendix J. Those for experiments 10 and 11 are in Appendix K. They are labeled according to surround luminance, but it should be understood that the variable under study was illuminance; both surround and sample were varied together. All samples were at a luminance factor of 0.20.

The data of Appendices J and K do not show systematic shifts in hue with decreasing illuminance for either D_{65} or A adaptation. That is, there is no significant shift in hue from the 1,000 $cd \cdot m^{-2}$ condition to either 500 or 200 $cd \cdot m^{-2}$ conditions. Hue shifts might be predicted from the Bezold-Brucke effect. However, studies of Bezold-Brucke shifts typically have involved a bipartite field presented in the aperture mode of appearance with retinal illuminances of about 1,000 and 100 trolands. Dominant wavelength of one half of the bipartite field is changed to effect a hue match with the other (usually higher luminance) half of the field, using either steady or brief flashes of stimulus presentation. The nature of shifts measured in this way depends to a large extent upon viewing time and induction of the bipartite halves (v., Boynton and Gordon 1965)[42]. In the research described here, however, focal stimuli had retinal illuminances of about 2,500 trolands down to 600 trolands as seen against extensive surrounds of approximately 12,500 trolands down to 3,500 trolands. The levels of retinal illuminance used here were, then, higher than in the typical Bezold-Brucke experiment (e.g., Purdy 1931)[273].

In addition, the focal stimuli here were under heavy induction from the surround; all samples had luminance factors of 0.20. These samples were presented as surface colors rather than aperture colors. The range of retinal illuminances for the samples was less than 5:1 rather than the more typical 10:1 of Bezold-Brucke studies.

There are, then, significant differences between the conditions of the present study and representative experiments concerned with Bezold-Brucke hue shifts. Considering these differences, there is no compelling reason to expect that previous work should predict the results of this experiment. In any event, it is clear that the data collected here do not show large hue shifts with variation in luminance (illuminance) over the range involved in this experiment. The tables of Appendices J and K indicate the same results for both color temperatures of adapting illumination.

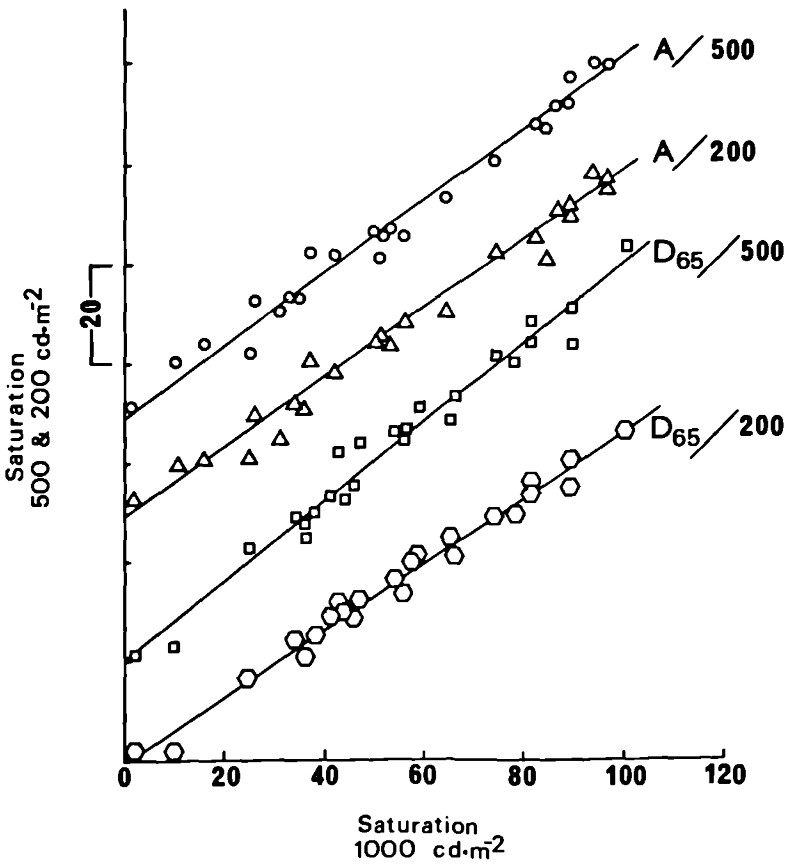
Quite a different result obtained for saturation, however. The data of Appendices J and K show that absolute saturation was heavily dependent on illuminance. Figure 37 (top) provides a graphical display of this evidence. In that graph, linear relations may be seen between arithmetic values of saturation at either of the two illuminance conditions and arithmetic values of saturation for the illuminance yielding a 1,000 $cd{\cdot}m^{-2}$ surround. The relations are displaced vertically for clarity. In all cases, the slopes are less than unity. The slopes of the 200 $cd{\cdot}m^{-2}$ functions are less than those of the 500 $cd{\cdot}m^{-2}$. Table XIII sets forth linear regression equations (and coefficients of determination) for those relations.

The average slopes, over both color temperatures, are about 0.76 for the 500 $cd{\cdot}m^{-2}$ conditions and 0.68 for the 200 $cd{\cdot}m^{-2}$ cases. Expressed as saturation factors, this is:

$$S_f = 0.184\ L_s^{0.236} \qquad (20)$$

where L_s is the surround luminance and S_f is saturation factor for a 0.20 luminance factor (Munsell Value 5) sample. That function is plotted at the bottom of Fig-

Illuminance Effect



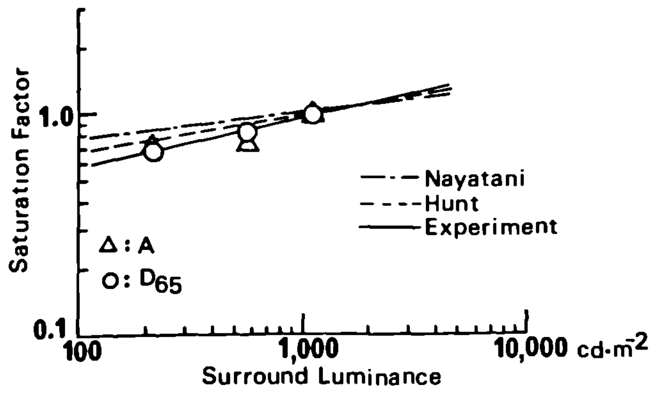


Figure 37

ure 37 as the solid line.

Table XIII

Saturation Over Illuminance

D_{65} Adaptation:

$$S_{500s} = 0.802\ S_{1000s} + 0.057 \quad (r^2 = 0.97)$$

$$S_{200s} = 0.668\ S_{1000s} - 0.282 \quad (r^2 = 0.98)$$

A Adaptation:

$$S_{500s} = 0.707\ S_{1000s} + 0.050 \quad (r^2 = 0.98)$$

$$S_{200s} = 0.686\ S_{1000s} - 0.588 \quad (r^2 = 0.98)$$

Two other functions are included in the bottom graph of Figure 37 for purposes of comparison. These are functions for saturation factors of surface colors worked out by Nayatani (v., Takahama et al 1975)[324] and by Hunt (1976)[159] from experimental data originally published by Hunt (1950)[153]. Expressed in comparable form to Equation 20, these would be:

Nayatani: $$S_f = 0.452\ L^{0.115} \qquad (21)$$

Hunt: $$S_f = 0.619\ L^{0.164} \qquad (22)$$

The present results suggest that absolute saturation varies roughly according to the 1/4 power of illuminance rather than the approximately 1/6 to 1/8 power estimated by Hunt and Nayatani, respectively. Of more interest than the exact level of exponent, is the fact that the same general kinds of relationship may be found in such different approaches to the problem.

Clearly, saturation is highly dependent on level of illumination. Apparently, the color temperature of that illumination - at least over the range from D_{65} to A illuminants - does not make very much difference to the nature of the illuminance-dependence. As with luminance factor effects, we see that hue is rather insensitive to variations in stimulation, but saturation is quite sensitive to changes in the character of the surface color array and its illumination.

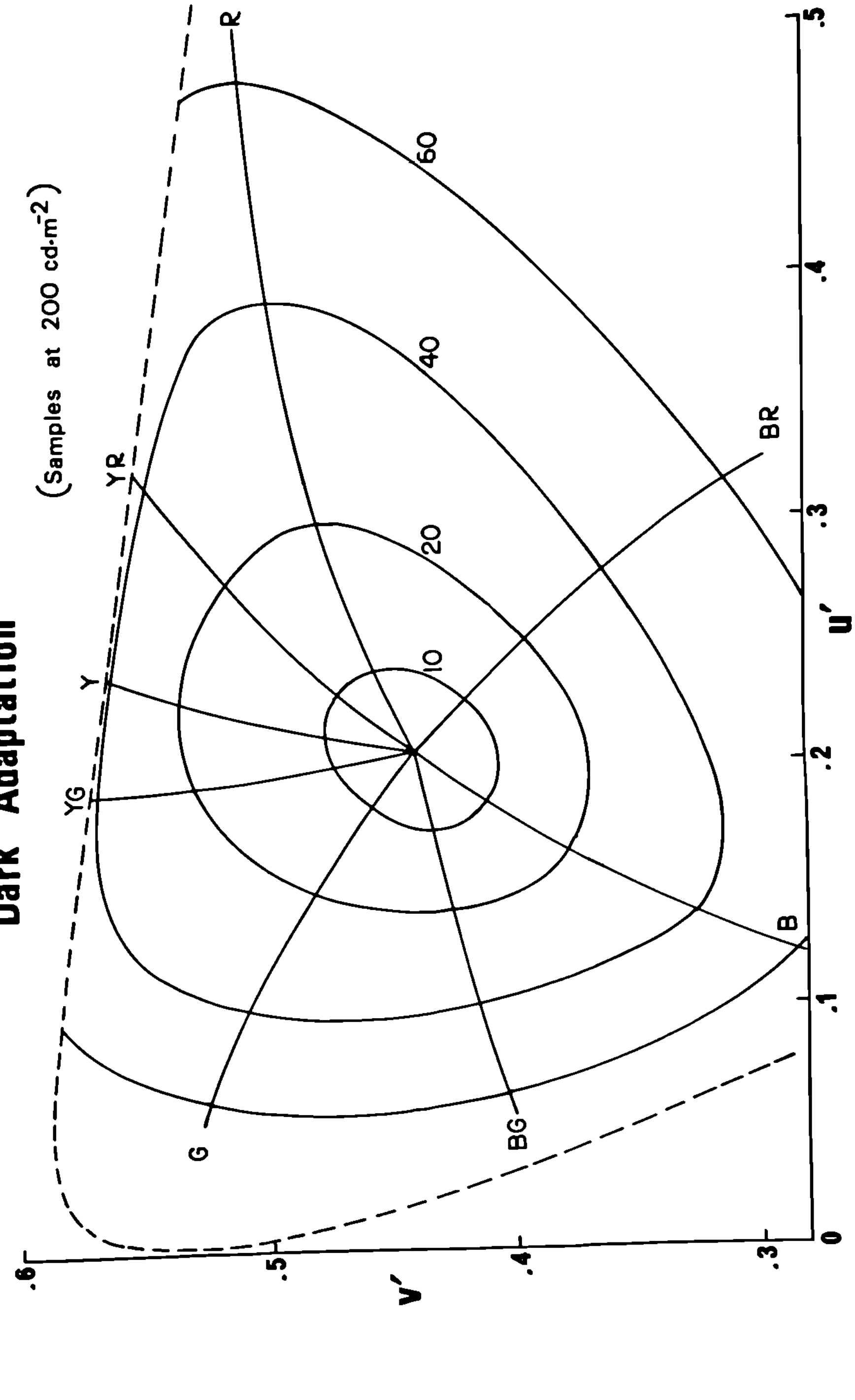
Effect of surround induction

Three observers (A, C, and E) scaled hue, absolute saturation and brightness in experiment 12 of Table VII on page 101. In that experiment, the 24 stimuli were presented without an illuminated surround; i.e., with dark adaptation. Approximately 40 minutes of dark adaptation preceded commencement of sample presentation. The stimuli all had luminances of 200 $cd \cdot m^{-2}$. They were presented according to the same timing sequence as used in the other 11 experiments.

Results are tabulated in Appendix L. Figure 38 illustrates isohue and isosaturation contours determined from this experiment arrayed in CIE 1976 u',v' coordinates. In this case, the contours were determined by averaging in the u',v' chromaticity diagram; as had been done only for experiment 1.

The general shapes of those contours are similar to the ones corresponding to other experiments in this series. However, the saturation contours are greatly expanded compared with the one relating to saturation of surface colors with white-appearing surrounds. That means that for the conditions of this investigation saturation of a constant-chromaticity stimulus is much lower with a dark surround than it is with a light surround. This has been noted before (e.g., Hunt 1950; Pitt and Winter 1974; Breneman 1976)[153, 266,48] with varying extents depending upon the amount of induction provided by the viewing conditions.

Figure 39 compares the extent of effect found here with that reported by Pitt and Winter (1974)[266] for simple fields. In that diagram, the open circles represent 200 $cd \cdot m^{-2}$ stimuli of saturation 40 and various hues as seen against a D_{65}-illuminated surround of 1,000 $cd \cdot m^{-2}$. The closed circles are for 200 $cd \cdot m^{-2}$ stimuli of the same hues and saturations but as seen with a dark surround. The dashed arrows relate to the highest purity samples used in the Pitt-Winter study. Arrow-tails are for light surrounds and arrow-



Dark Adaptation
(Samples at 200 cd·m⁻²)
R
YR
Y
YG
G
BG
B
BR
10
20
40
60
u′
v′
0
.1
.2
.3
.4
.5
.6

Figure 38

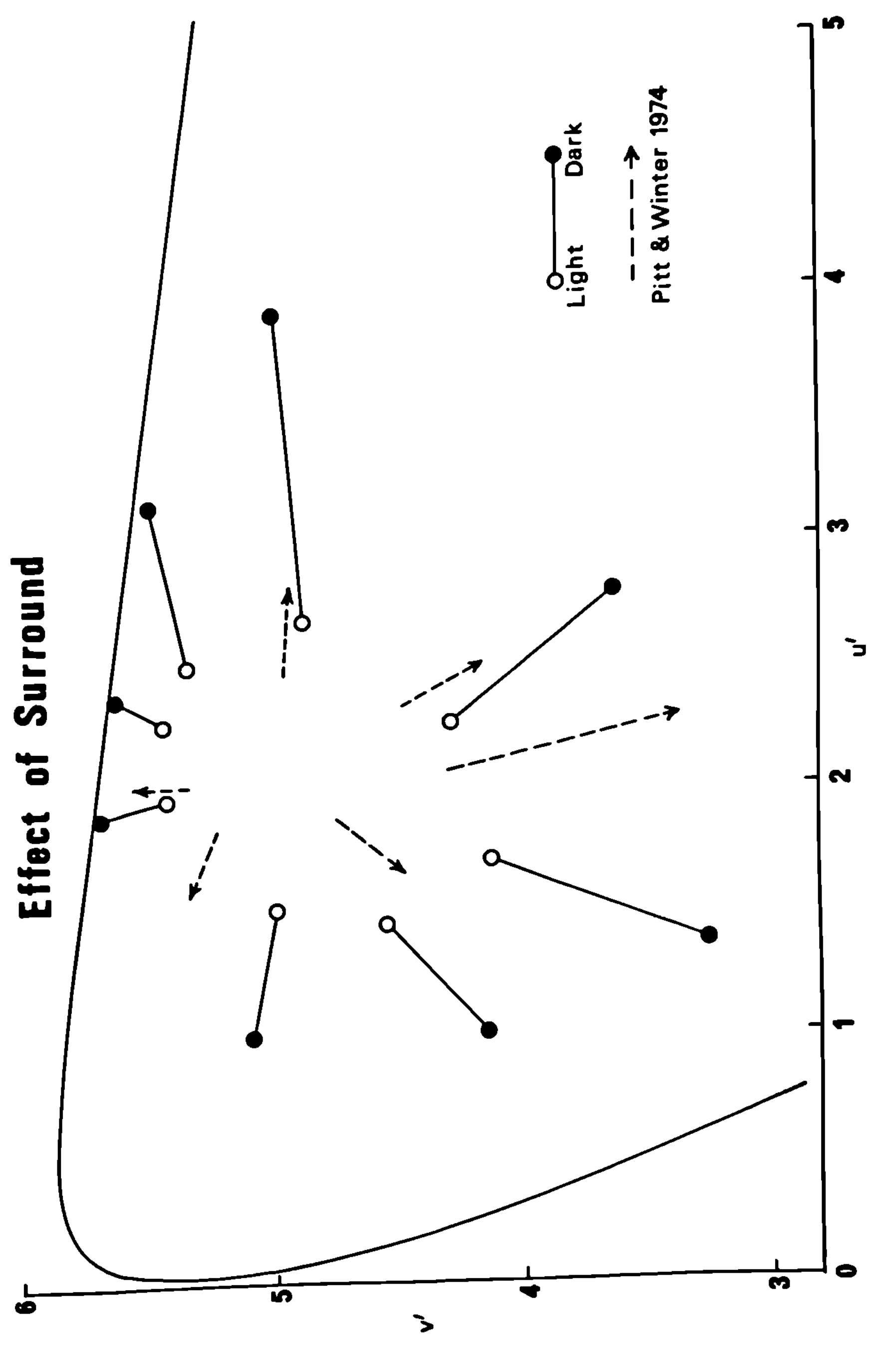

Effect of Surround
Light
Dark
Pitt & Winter 1974
u'
v'
0
1
2
3
4
5
3
4
5
6

Figure 39

heads are for dark surrounds.

Considering that these were two quite different experiments, using different color temperature illuminants for the light-surround adaptation conditions, the general agreement between the two sets of results is very good. Obviously, saturation is heavily influenced by the presence or absence of the inducing surround.

In this instance hue was also significantly altered by the absence of a light surround. The hue contours of Figure 38 are different from those shown in Figures 13, 14, and 15 for other conditions of adaptation. It is probably incorrect to ascribe this difference to luminance induction effects, however. The experiments on the effect of luminance factor showed that hue is not greatly influenced by relative level of induction. It is, however, influenced by the color temperature - or, in other terms, by relative receptor sensitivity evoked by the spectral selectivity of the illumination. Accordingly, the shapes of hue contours in Figure 38 should probably be taken to represent the result of essentially unbiased or neutral sensitivities of the chromatic mechanism for vision.

Lightness and brightness

Both lightness and brightness attributes of color appearance have been studied extensively in other experiments. For that reason, they were not subjected to detailed investigation here. However, some data on lightness and brightness were collected in parts of this study. The bulk of these data are for lightness as scaled in the magnitude production phases of the work. Figure 40 summarizes those results.

In Figure 40a log lightness is plotted against log luminance (in $cd \cdot m^{-2}$) for 5 different chromatic conditions of stimulation: (N) neutral or gray-appearing samples, ($\tilde{Y}$) yellowish-appearing samples, ($\tilde{G}$) greenish-appearing, ($\tilde{R}$) reddish-appearing, and ($\tilde{B}$) bluish-appearing samples. All five functions exhibit typical induction characteristics. That is, they are all nonlinear in double logarithmic coordinates. They are

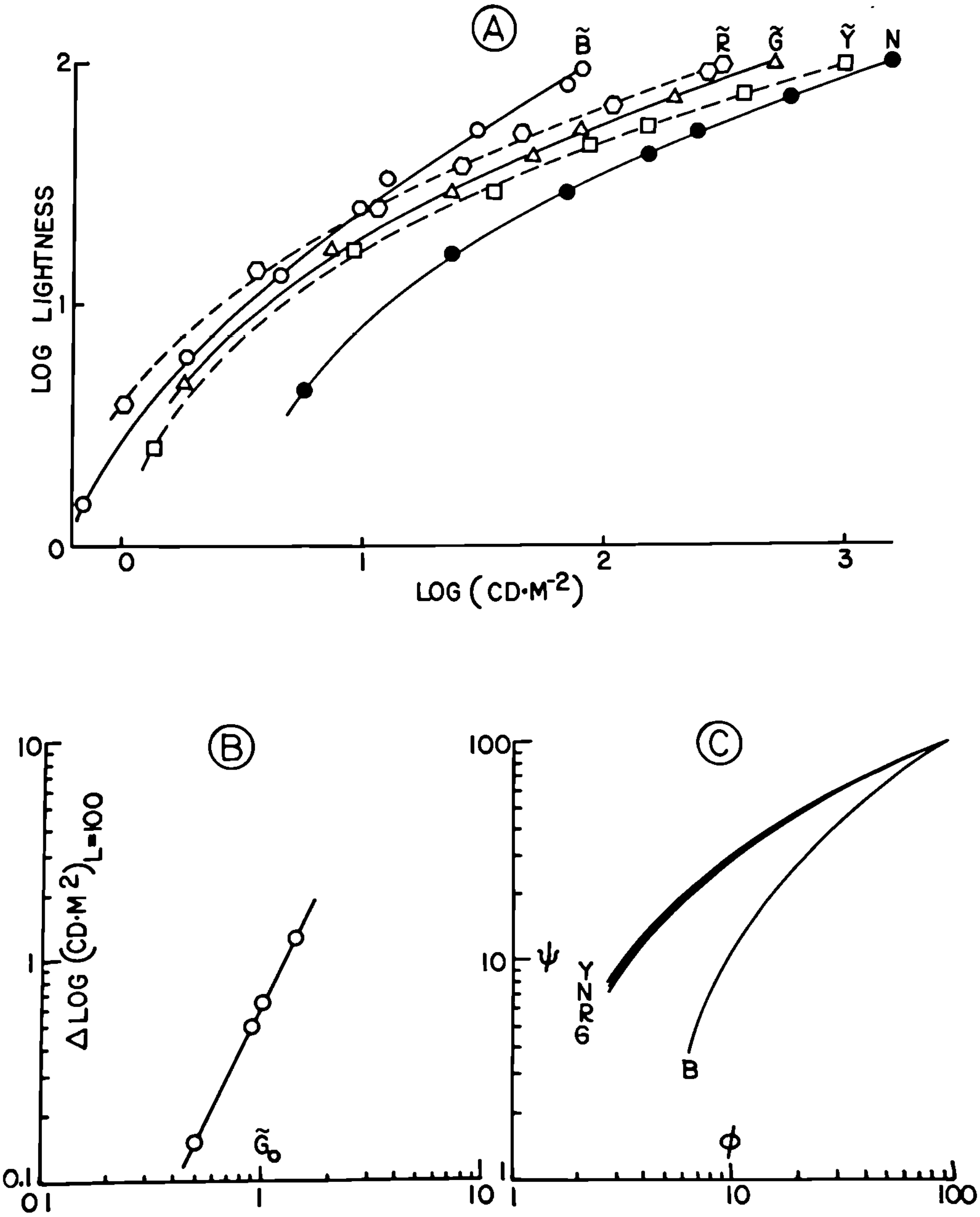
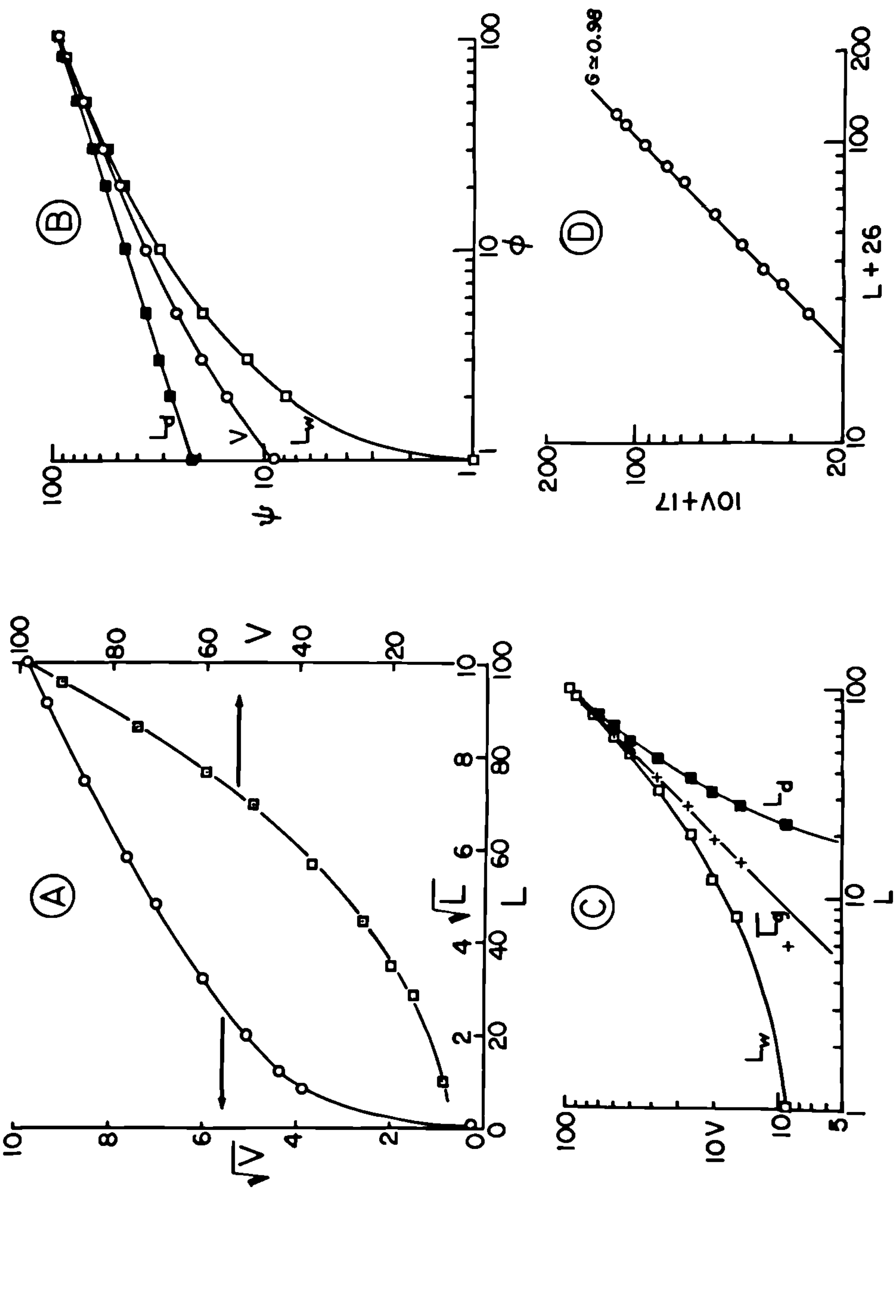


Figure 40



igure 41

displaced along the luminance axis, indicating that the luminance required for a brightness match with the D_{65} white-appearing surround differed according to the chromaticity of the sample. These differences represent the extent of Helmholtz-Kohlrausch effect observed with these samples.

The differences in log luminance by which the curves are displaced have been plotted against Evans' (1974)[93] zero gray content (G_o) values corresponding to the dominant wavelengths of the samples in Figure 40b. Since the points describe a straight line in those double logarithmic coordinates, it may be inferred that the log luminance separation of the lightness functions resulting from Helmholtz-Kohlrausch effects is related to G_o by a power function.

Figure 40c illustrates the same lightness functions plotted against relative luminance; i.e., normalized to eliminate the Helmholtz-Kohlrausch differences. That figure facilitates comparison of the relative shapes of the lightness functions. All except the bluish-appearing samples yielded essentially the same shape of lightness function. The average gradients of the functions are all somewhat higher than that of the Munsell Value function, however.

Figure 41a shows scaled lightness of neutral samples in relation to predicted Munsell Values for them. Both square-root of Value versus lightness and square-root of lightness against Value are shown. If the two functions differed according to typical relations between magnitude and interval scales, we would expect one of those functions to be linear. Obviously, neither is linear. The graph of Figure 41b makes the reason for this immediately clear. The curve labeled V is for Munsell Value (ψ) versus relative luminance (ϕ). That labeled L_w is for scaled lightness (ψ) with a white-appearing surround. Both functions are nonlinear in the double logarithmic coordinates of the graph. The L_w function exhibits greater negative curvature. This implies that there was greater induction under the viewing conditions of this experiment than is the case implicit to the Munsell data. A third curve has been included in Figure 41b for comparison; labeled L_d. That curve illustrates the normalized brightness function derived under the dark surround conditions of this experiment. It is a straight line with a slope close to 1/3; implying that there was essentially no induction for that viewing condition. The Munsell Value function lies between the curves L_d and L_w.

Munsell Value (x10) is plotted against lightness from curves L_d and L_w in Figure 41c. Both relationships are nonlinear. However, the geometric mean of those two relations (labeled $\acute{L}_g$ in Figure 41c) is very close to being linearly related to Munsell Value. The two-fold implication is that (1) Munsell Value comprises a magnitude scale of lightness, and (2) the differences exhibited between lightness as scaled here and Munsell Value are associated primarily with differences in induction brought about by unequal conditions of viewing. Thus, if response corrected data for Value and scaled lightness were to be compared, we should expect a linear relation.

This is, in fact, the result as illustrated in Figure 41d. In that graph, Value (x10) + 17 is plotted against lightness + 26; where lightness is with the illuminated surround. The linear relationship has a slope of 0.98, which is close enough to unity to support the inferences enumerated above.

Thus, both lightness and brightness scaled in these experiments are consistent with other data on scales of these attributes. Further, observers in this study scaled lightnesses in such a manner as to reflect the extent of brightness discrepancies with luminance that are associated with the Helmholtz-Kohlrausch effect. Those discrepancies are systematically related to Evans' G_o values of what he called 'brilliance'. This result argues against his contention that lightness is the perception of relative luminance and that observers see equality of lightness between surround and sample as equality of luminances (Evans 1974, pp.117-119)[93]. The observers who participated in this study, at least, do not respond in the way Evans claims. His 'brilliance' would be directly related to lightness of surface colors with luminance factors less than unity, according to the observers in this work. This conclusion should not be taken to mean that brilliance is the same as lightness. Rather, we may conclude that at least one of the components of brilliance is that attribute which observers here scaled as lightness.

V. Discussion

The results described in the foregoing sections indicate that an observer's chromatic responses undergo significant changes when the conditions for chromatic adaptation are altered. This may be seen in the systematic variations of hue appearances of stimuli and, particularly, in the variations in saturations of stimuli when the conditions of adaptation are changed. These variations will be discussed in this section in an attempt to derive a general structure for analyzing the influence of chromatic adaptation on color appearance. Particular emphasis will be placed on (a) saturation and purity relationships, (b) systematic changes in color appearance contours, (c) relations between dominant wavelength and hue, and (d) distinctions between absolute and relative attributes of color appearance. Finally, the present results will be compared to results of some other experiments by different workers who have undertaken to study chromatic adaptation.

Chromatic purity and saturation

A number of previous studies of chromatic adaptation have attempted to determine the fundamental sensitivities of the chromatic visual mechanism. This research has not directly attempted to uncover such functions. Rather, it has been concerned with changes in the chromatic response characteristics of observers by studying the influence of chromatic adaptation on color appearance. Those chromatic responses may be considered derivatives of the underlying fundamental sensitivities. Figure 42 has been constructed to illustrate this point.

Figure 42a shows a set of relative fundamental sensitivities (or 'Grundempfindungen') proposed by König (1886; König and Dieterici 1893)[210,211]. They may be described in terms of the CIE 1931 Standard Observer as:

$$\begin{aligned} \bar{r} &= 0.0713\bar{x} + 0.9625\bar{y} - 0.0147\bar{z} \\ \bar{g} &= -0.3952\bar{x} + 1.1668\bar{y} + 0.0815\bar{z} \\ \bar{b} &= 0.0000\bar{x} + 0.0000\bar{y} + 0.5610\bar{z} \end{aligned} \qquad (23)$$

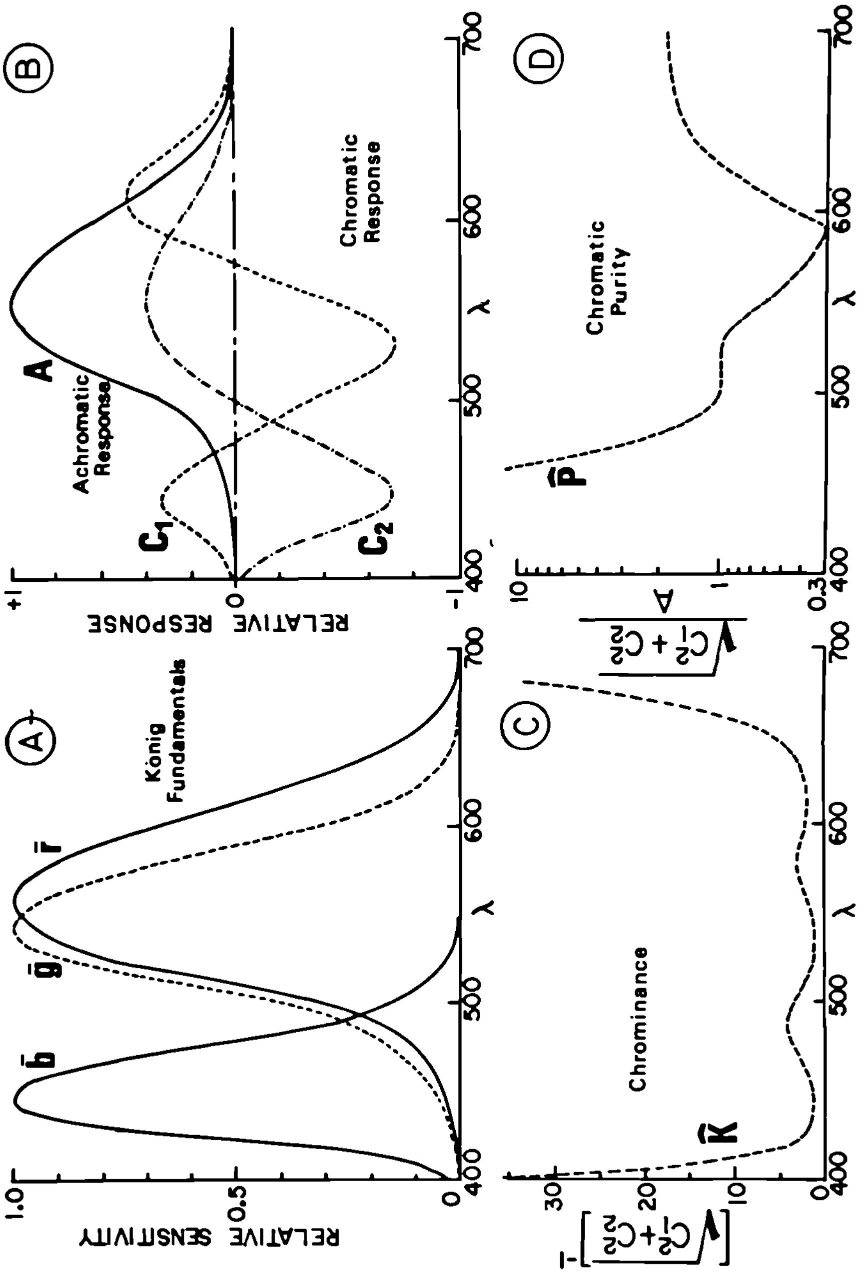

A
B
C
D
König Fundamentals
RELATIVE SENSITIVITY
1.0
0.5
0
400
500
600
700
λ
Achromatic Response
Chromatic Response
RELATIVE RESPONSE
+1
-1
C_1
C_2
Chrominance
$\tilde{K}$
30
20
10
Chromatic Purity
$\tilde{P}$
0.3

Figure 42

where $\bar{r},\bar{g},\bar{b}$ stand for the fundamental spectral distribution coefficents. The values of these fundamentals from 400 to 760 nm are tabluated at 10 nm intervals in Table 5.5 of Wyszecki and Stiles (1967, page 414)[373]. These curves were derived in an attempt to describe the color mixture data of normal trichromats and, with certain assumptions, of protanopes and deuteranopes. They are used here only as examples that are typical of one class of fundamentals that has been proposed. No special claim is made for them here beyond their being reasonably representative of their class.

Those fundamental sensitivity functions may be used to derive a set of opponent chromatic response functions (Jameson and Hurvich 1955,1968)[177,182]. Two chromatic response functions which are linearly related to the König $\bar{r},\bar{g},\bar{b}$ values and, hence, to the CIE 1931 Standard Observer, are as follows (Jameson 1972, p.395)[176]:

$$\begin{aligned} c_1 &= 1.66\bar{r} - 2.23\bar{g} + 0.37\bar{b} \\ c_2 &= 0.34\bar{r} + 0.06\bar{g} - 0.71\bar{b} \end{aligned} \qquad (24)$$

and an achromatic function derived from the same fundamentals which is essentially equal to the CIE 1924 Standard Photometric Observer is:

$$A = 0.85\bar{r} + 0.15\bar{g} + 0.00\bar{b} \qquad (25)$$

Figure 42b illustrates these relative response functions.

The relationships of the response functions indicate that chromatic power varies considerably over wavelength. One expression of that chromatic power has been called 'chrominance' (e.g., Boynton 1975, pp.342-343)[39] and may be stated by the equation:

$$\hat{K} = \sqrt{(c_1)^2 + (c_2)^2} \qquad (26)$$

A chrominance function, following Equation 26, derived from the König fundamentals is illustrated in Figure 42c.

Finally, 'chromatic purity' may be expressed as the ratio of chrominance to achromatic response:

$$\hat{P} = \frac{\sqrt{(c_1)^2 + (c_2)^2}}{A} \qquad (27)$$

and that function is illustrated in Figure 42d.

Equation 27 is only one of the ways in which chromatic purity could be expressed. For example, chromatic purity could be taken as the ratio of chrominance to total (achromatic + chromatic) response, in which case the curve of Figure 42d would be slightly more leptokurtic. However, its general shape and wavelength for minimum would still be the same. The relationship of Equation 27 is used only to illustrate the point that several derivative functions of the fundamentals may be computed and each of them implies certain relations among components of sensation.

It is the concordance of experimental data collected with the implications of these general functions of sensation that will be discussed here. In other words, we will attempt to determine how the present data may be interpreted as changes in representative sensory response characteristics based on an arbitrary, but reasonable, set of fundamentals.

We may examine the question of how the present experimental data relate to linear von Kries-type adaptation theory by comparing such predictions for chromatic purity with the purities actually found in the experiment. Figure 43 facilitates such a comparison. Chromatic response functions are shown at the top of that figure for each of the three color temperature conditions investigated. Those functions are derived by integrating the $\bar{r}, \bar{g}, \bar{b}$ fundamentals with the spectral power distributions of the three illuminants used for adaptation. They were arbitrarily normalized so that the $\bar{g}$ functions remained at constant integrated value. The chromatic purity functions computed from those adaptationally adjusted values are shown as the dashed curves in the lower graphs of Figure 43. They are expressed as reciprocal chromatic purities versus wavelength. Open circles represent the colorimetric purities (x10) for each of several dominant wavelengths as found in the experiment (samples were of luminance factor 0.20, saturation 40, and with a surround of 1,000 $cd \cdot m^{-2}$).

Although the similarity between experimental and

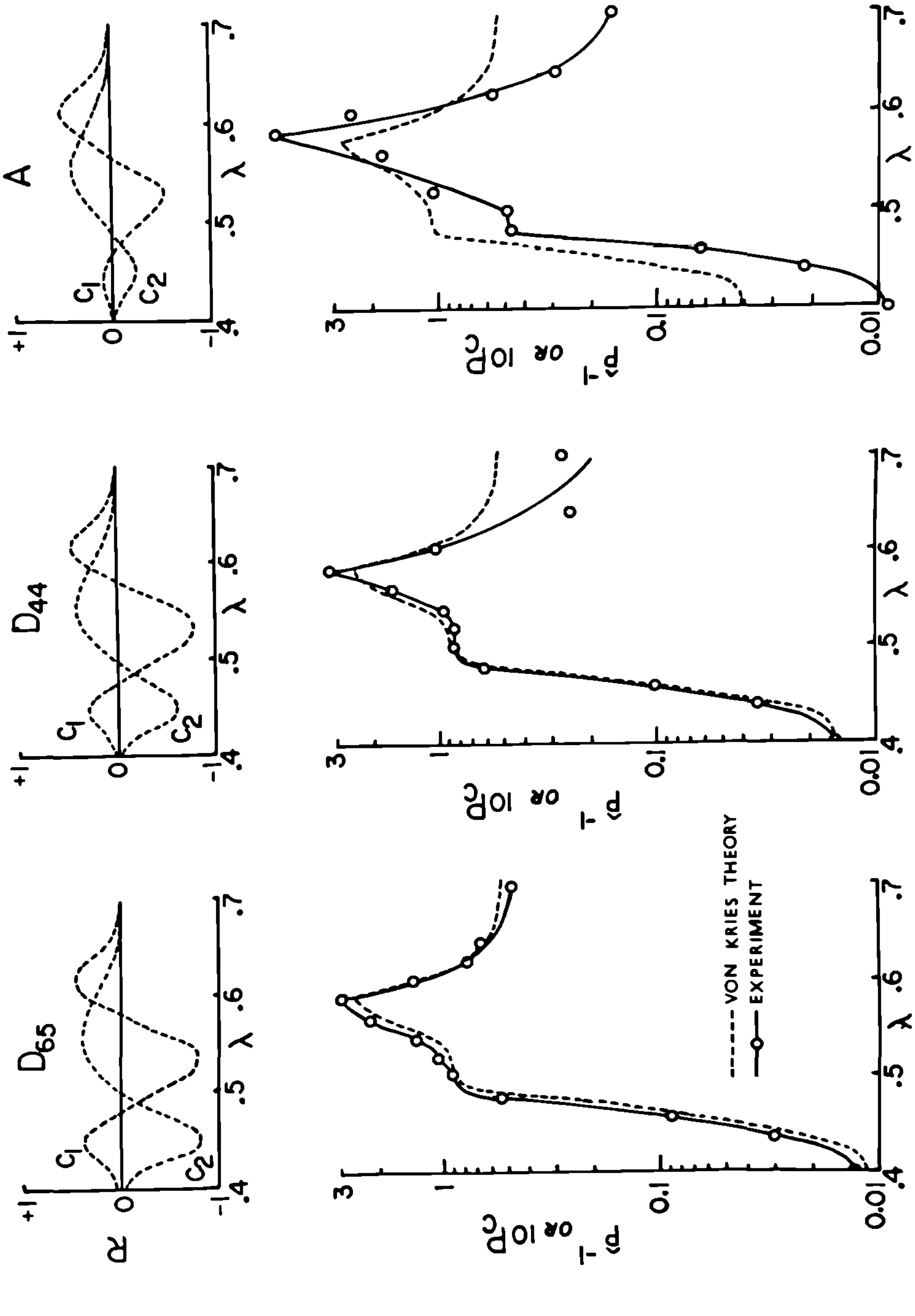


Figure 43

theoretical data is good for D_{65}, the agreement is not very impressive for the other two illuminants. The agreement seems to decrease with decreasing color temperature.

Figure 43 suggests that the results of this study do not tend to obey a linear rule for chromatic adaptation. However, if we attend to the similarities, rather than differences, it is evident that chromatic purity does seem to express a kind of response characteristic that is not unlike the spectral saturation functions determined in this work. It was noted earlier that there is an approximate but systematic relationship between saturation exponents and chromatic purity over changes in adaptation. By applying that power relation to chromatic purity, it is possible to derive a series of power transforms for chromatic purity with much greater consistency with experimentally determined purities. That is, the chromatic purity function may be compressed or expanded to fit the colorimetric purities of scaled saturation data. Those experimental colorimetric purities are listed in Tables XIV, XV, and XVI.

Table XIV

D_{65} Colorimetric Purities

Wavelength	Saturation			
(nm)	20	40	60	80
400	0.13	0.47	0.80	1.45
440	0.29	1.08	1.40	3.42
460	0.88	3.25	5.69	10.50
480	5.26	18.37	34.14	64.86
500	9.00	29.14	46.33	64.09
520	10.26	32.54	49.41	72.38
540	13.18	41.72	55.19	90.87
560	21.49	62.87	91.12	+
580	29.90	75.36	95.98	+
600	12.27	38.74	64.75	94.58
620	7.63	23.73	39.31	65.36
640	6.63	18.92	32.89	53.50
700	4.78	15.91	32.24	50.79

+ = over 100

Colorimetric purities have been multiplied by a factor of 100 in these tables.

Table XV

D_{44} Colorimetric Purities

Wavelength (nm)	Saturation 20	40	60	80
400	0.15	0.51	1.02	1.89
440	0.36	1.16	2.36	4.36
460	1.05	3.40	7.02	12.70
480	6.45	19.50	39.80	64.90
500	8.70	16.70	37.20	53.20
520	8.63	24.00	40.80	61.80
540	9.68	30.40	51.70	78.10
560	16.90	47.00	77.50	+
580	33.40	75.80	+	+
600	10.60	33.30	66.50	+
620	1.58	18.70	39.90	69.30
640	2.50	12.70	31.50	58.10
700	2.79	11.10	27.60	54.70

Table XVI

A Colorimetric Purities

Wavlength (nm)	Saturation 20	40	60	80
400	0.09	0.34	0.69	1.31
440	0.22	0.78	1.59	3.07
460	0.64	2.31	4.60	8.94
480	4.75	13.60	25.90	59.90
500	4.90	11.30	37.50	64.10
520	10.60	17.90	33.80	51.00
540	12.10	22.60	39.60	62.50
560	18.00	30.10	57.20	90.20
580	50.70	99.00	+	+
600	25.00	38.40	64.90	91.00
620	5.70	18.00	35.00	54.10
640	2.90	10.90	36.20	53.30
700	1.64	12.60	29.20	40.40

Values of $\hat{P}^{-1}$ (x100) are listed in Table XVII.

Table XVII

Chromatic Purities for 3 Adaptations

Wavlength (nm)	D_{65}	D_{44}	A
400	1.21	1.60	3.73
420	1.21	1.60	4.22
440	2.64	3.52	9.43
460	7.63	10.4	9.43
480	43.9	58.1	105.
500	90.9	88.5	108.

(continued)

(Table XVII continued)

Wavelength (nm)	D_{65}	D_{44}	A
520	90.9	91.7	123.
540	110.	113.	157.
560	208.	187.	243.
580	249.	250.	223.
600	136.	133.	113.
620	78.7	78.1	73.5
640	62.9	62.9	61.0
660	57.5	57.5	56.5
680	55.9	55.9	55.0
700	55.6	55.6	55.6

- -

The data of these tables may be related to one another through power functions of the form:

$$P_c = a(\hat{P}^{-1})^b \qquad (28)$$

Values of the constants in Equation 28, together with the coefficients of determination (r^2), are listed in Table XVIII.

- -

Table XVIII

Purity Relations

Adaptation		S=20	S=40	S=60	S=80
D_{65}	a :	10.533	32.367	50.912	83.705
	b :	0.993	0.939	0.926	0.877
	r^2:	0.996	0.995	0.990	0.983
D_{44}	a :	7.469	25.071	48.303	79.288
	b :	0.959	0.939	0.905	0.869
	r^2:	0.892	0.985	0.992	0.983
A	a :	7.457	18.295	34.986	56.403
	b :	1.350	1.146	1.082	1.027
	r^2:	0.910	0.910	0.912	0.925

- -

The coefficients of determination, r^2, are all reasonably high, indicating that the data are well characterized by the power relation. The fit is best for D_{65}. There is a systematic relation between the size of the constants and saturation level. Scale factors increase with saturation but exponents decrease with saturation. This indicates that the P_c functions of of wavelength become higher in value but flatter over wavelength as saturation increases.

Tables XIX, XX, and XXI list data computed from these power relations. Those data may be compared with the data of Tables XIV, XV, and XVI to see the relationship between the predicted values and those determined experimentally.

Table XIX

D_{65} Adjusted Chromatic Purity

Wavelength (nm)	S=20	S=40	S=60	S=80
400	0.132	0.513	0.856	1.74
420	0.132	0.513	0.856	1.74
440	0.286	1.07	1.76	3.45
460	0.819	2.89	4.71	8.76
480	4.65	14.9	23.7	40.6
500	9.58	29.6	46.6	77.0
520	9.58	29.6	46.6	77.0
540	11.6	35.4	55.6	91.0
560	21.8	64.3	100.	159.
580	26.1	76.3	119.	187.
600	14.3	43.1	67.5	109.
620	8.31	25.9	40.8	67.9
640	6.65	20.9	33.1	55.7
660	6.08	19.2	30.5	51.5
680	5.91	18.7	29.7	50.2
700	5.88	18.6	29.6	50.0

Table XX

D_{44} Adjusted Chromatic Purity

Wavelength (nm)	S=20	S=40	S=60	S=80
400	0.141	0.516	1.15	2.18
420	0.141	0.516	1.15	2.18
440	0.301	1.08	2.34	4.33
460	0.850	2.99	6.21	11.1
480	4.44	15.1	29.6	49.5
500	6.64	22.4	43.2	71.3
520	6.88	23.1	44.7	73.6
540	8.36	28.0	53.7	87.8
560	13.6	45.1	85.1	137.
580	18.0	59.3	111.	176.
600	9.80	32.7	62.4	101.
620	5.89	19.9	38.6	64.0
640	4.79	16.2	31.7	53.0
660	4.39	14.9	29.3	49.0
680	4.27	14.5	28.5	47.8
700	4.25	14.4	28.4	47.6

Table XXI

A Adjusted Chromatic Purity

Wavelength (nm)	S=20	S=40	S=60	S=80
400	0.088	0.423	0.995	1.92
420	0.104	0.487	1.14	2.18
440	0.307	1.22	2.72	4.99
460	0.307	1.22	2.72	4.99
480	7.99	19.4	37.0	59.4
500	8.31	20.0	38.1	61.2
520	9.87	23.2	43.8	69.8
540	13.7	30.6	56.9	89.5
560	24.7	50.5	91.3	140.
580	22.0	45.8	83.2	128.
600	8.81	21.1	40.0	64.0
620	4.92	12.9	25.1	41.1
640	3.82	10.4	20.5	33.9
660	3.45	9.51	18.9	31.4
680	3.32	9.21	18.3	30.5
700	3.37	9.33	18.5	30.8

Figure 44 has been drawn to illustrate the relation between computed and observed values for the D_{65} adaptation condition. The circles are P_c values determined experimentally. Dashed curves are the computed prediction functions. Truncation lines - corresponding to unit purity - are shown for each saturation level as labeled horizontal lines. Those lines intersect the computed functions for saturations of 60 and 80; implying that physical samples cannot be produced above those levels. In fact, the experimental points do not rise above those levels because it was impossible to produce samples of saturations higher than that.

The prediction curve and experimental data for saturation 80 describe a more shallow (platokurtic) function than is the case for saturation 20 which is leptokurtic by comparison. This result is an important supplement to information previously determined for saturation thresholds expressed as purity limens. The threshold problem has been approached in two different ways in past studies. Some workers have determined purity limens by adding spectral light to white-appearing light (e.g., Priest and Brickwedde 1938)[272]. Others have added white-appearing light to spectral stimuli

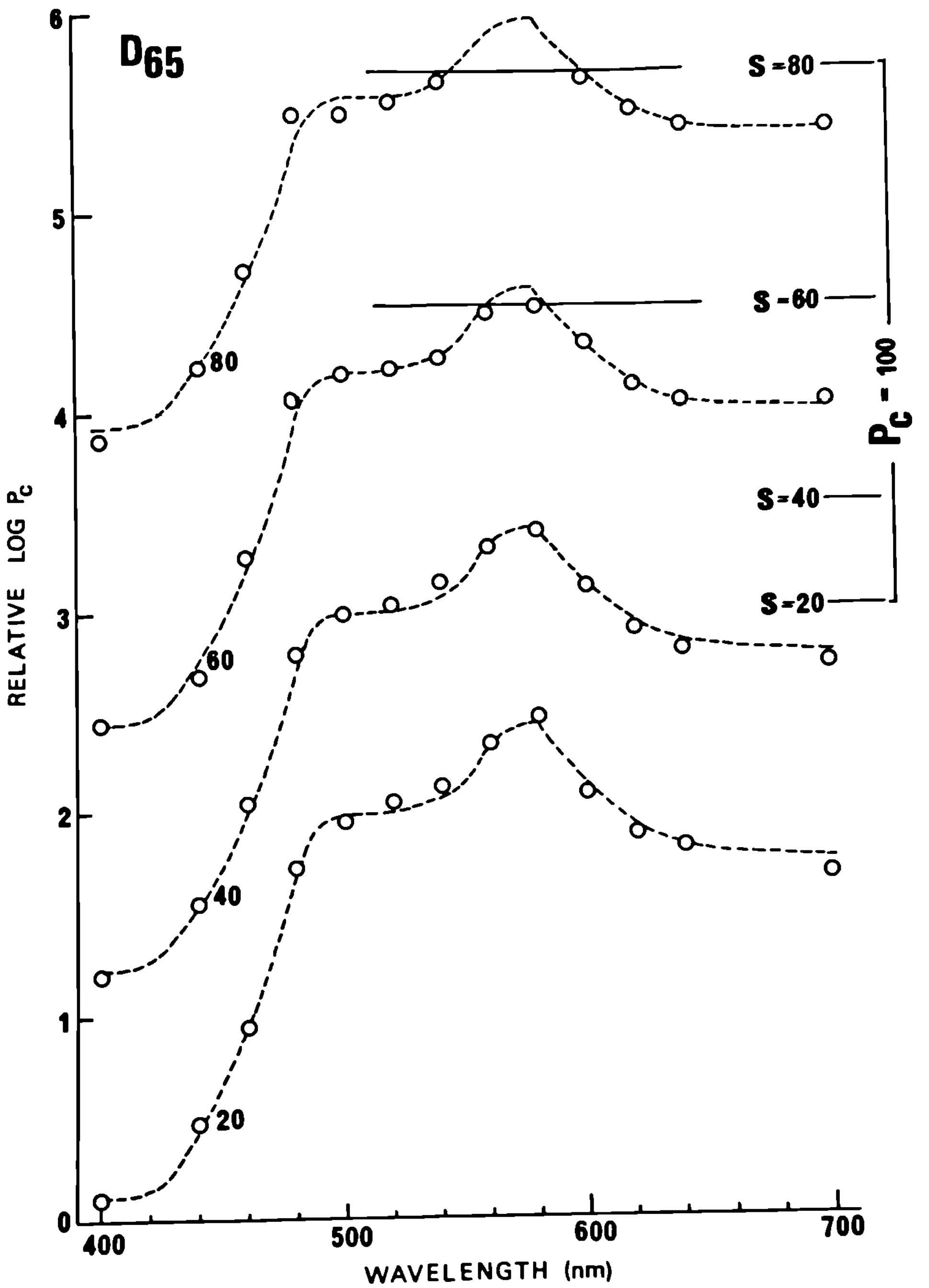

D65
RELATIVE LOG P_C
WAVELENGTH (nm)
S=80
S=60
S=40
S=20
P_C = 100
80
60
40
20
0
1
2
3
4
5
6
400
500
600
700

Figure 44

(e.g., Wright and Pitt 1935)[365]. The purity threshold functions are steep when approached from white. However, they are flatter when approached from the spectrum, although not necessarily perfectly flat (Kaiser, Comerford and Bodinger 1976)[194]. Stated in simple terms, the threshold purity function is more compressed at the spectrum than at the neutral point. That is precisely what the data of Figure 44 show. Moreover, that figure indicates a systematic flattening of the constant-saturation purity function throughout the entire range of colorimetric purities involved as the spectral condition is approached.

The rate of compression observed in these purity functions varies with chromatic adaptation. It increases as the correlated color temperature of the adapting light is decreased. The rate observed here is greatest for adaptation to illuminant A conditions, least for D_{65}, and D_{44} is intermediate.

Figure 45a is a graph of the relations between exponents, b, and scale factors, a, of the compression equations and saturation level. They are shown in double logarithmic coordinates. The constants of those power equations vary, themselves, as power functions of saturation. The relative rates of compression as the spectrum locus is approached may be seen in Figure 45b. Here the scale factors, a', and exponents, b', are taken with respect to the function for a saturation level of 20; a condition approaching achromatic. Those relative values may be expressed as differences in the percentage change of the constants for the three conditions, as shown in Figure 45c. D_{65} adaptation is used as an arbitrary reference. The relative change in compression equations, represented by the flattening of purity functions from near-neutral to near-spectral stimuli, varies approximately linearly with reciprocal megakelvins (or mireds, to use the older term).

Thus, color appearance changes brought about by variation in chromatic adaptation result in systematic changes in the relationship between colorimetric purity of stimuli and the saturations they elicit. We find

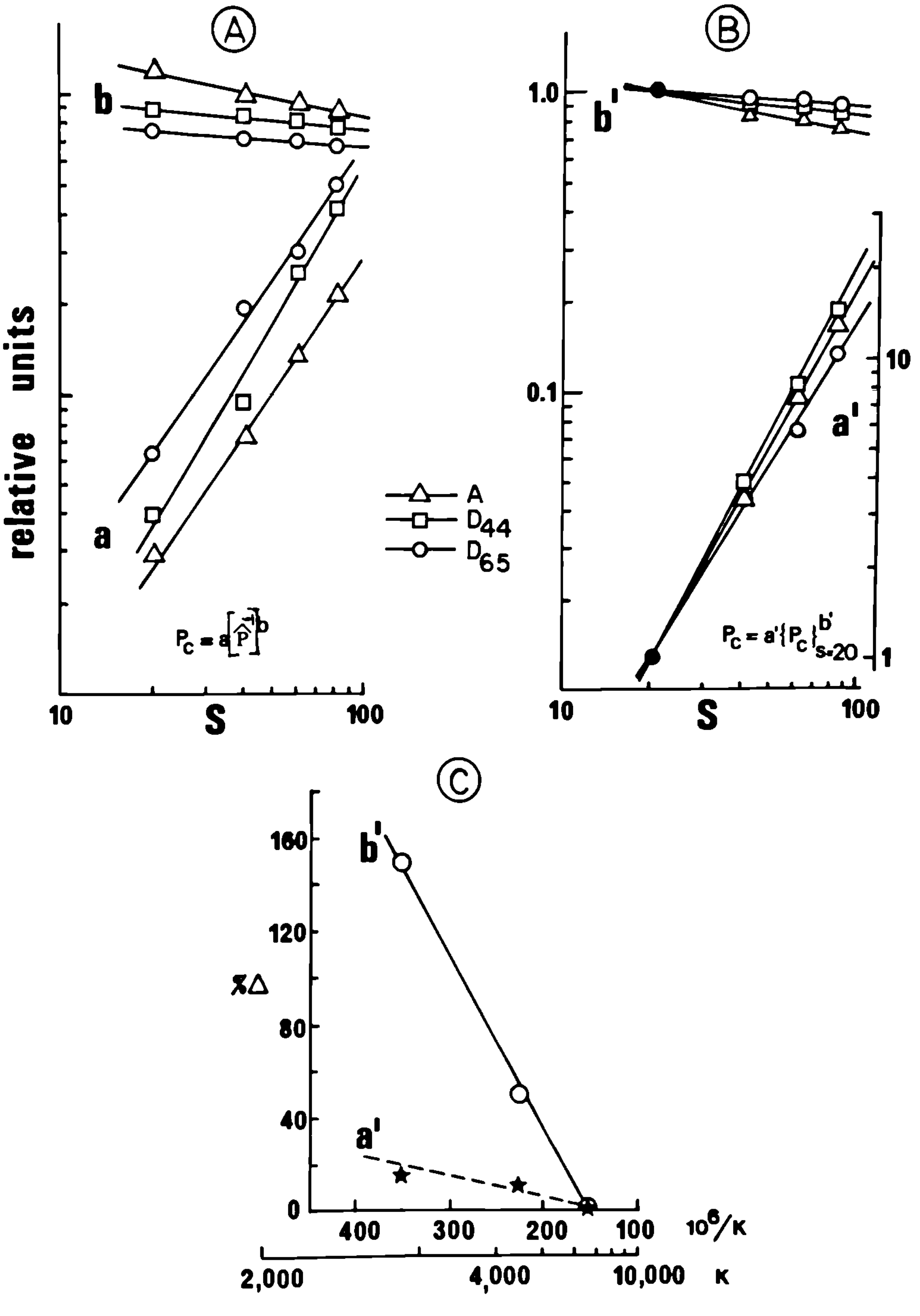

A
B
C
relative units
b
a
b'
a'
1.0
0.1
10
1
10
100
S
A
D44
D65
$P_c = a[\hat{P}^{-1}]^b$
$P_c = a'\{P_c\}^{b'}_{s=20}$
160
120
80
40
0
%Δ
400
300
200
100
$10^6/K$
2,000
4,000
10,000
K

Figure 45

that the purities of constant-saturation stimuli of different dominant wavelengths are closely predicted by power transforms of theoretical chromatic purity functions based on linear transform rules for chromatic adaptation. But the fact that (nonlinear) power transforms are required to describe the data, indicate that the linear model is not adequate by itself. Instead, a nonlinear or multi-stage model is implied by these data. In the process of deriving the data on which this inference is based, it has also come to light that there are two kinds of systematic relations between colorimetric purity and saturation that have not been noted previously. The first of these is that purity functions of dominant wavelength for constant saturation undergo continuous changes in compression over the entire range of purities from 0 to 1; and these changes are described as power functions of saturation level. Second, the rates of change in compression of purity functions vary with correlated color temperature of adapting lights; being greater at lower color temperatures in such a way that changes in compression are a linear function of the reciprocal of color temperature (i.e., reciprocal megakelvins).

As noted earlier in this report, a number of experimentally observed phenomena may be described by functions that mimic the shape of the chromatic purity function. A review of some of these studies has been made by Kaiser, Comerford and Biggin (1974)[193]. Two of them will be singled out here to illustrate the contention that saturation (or colorfulness) is related to both chromatic and achromatic intensiveness. In all probability, brightness has both chromatic and achromatic components (e.g., Guth and Lodge 1973; Kaiser, Herzberg and Boynton 1971; Kaiser and Comerford 1975)[119,195,192] so the two may be inextricably linked in the perception of how colorful a stimulus appears. Conversely, how bright a stimulus appears is related to how colorful it is.

One of the phenomena in which the dependence of brightness on chromaticness has long been noted is the Helmholtz-Koklrausch effect; where less luminance is required to match the brightness or lightness of a high-purity stimulus to that of a low-purity stimulus of the same dominant wavelength (e.g., Breneman 1958; Sanders and Wyszecki 1957,1958,1964; Wyszecki and Sanders 1957a,b)[46,291-293,371,372]. Kaiser and Kinney (1975)[196] reviewed and summarized the ratios of luminances for neutral (white-appearing) light to the luminances of chromatic-appearing lights in colorimetric mixtures of equal brightness as purity was increased for 16 dominant wavelengths of chromatic-appearing stimuli. Kaiser and Smith's (1972)[197] results are plotted in Figure 46. The data points are shown as circles. Data from Sanders and Wyszecki (1964)[293] are also included as triangles. It appears that most of the data might be described by equations that vary with dominant wavelength. For that reason, they were fitted with power functions of the form: $y = ax^b$. The parameter values and coefficients of determination are listed in Table XXII. Curves of the functions are shown in Figure 46 as dashed lines. Except for the two shortest wavelengths - 430 and 450 nm - the fit is quite good.

- -

Table XXII

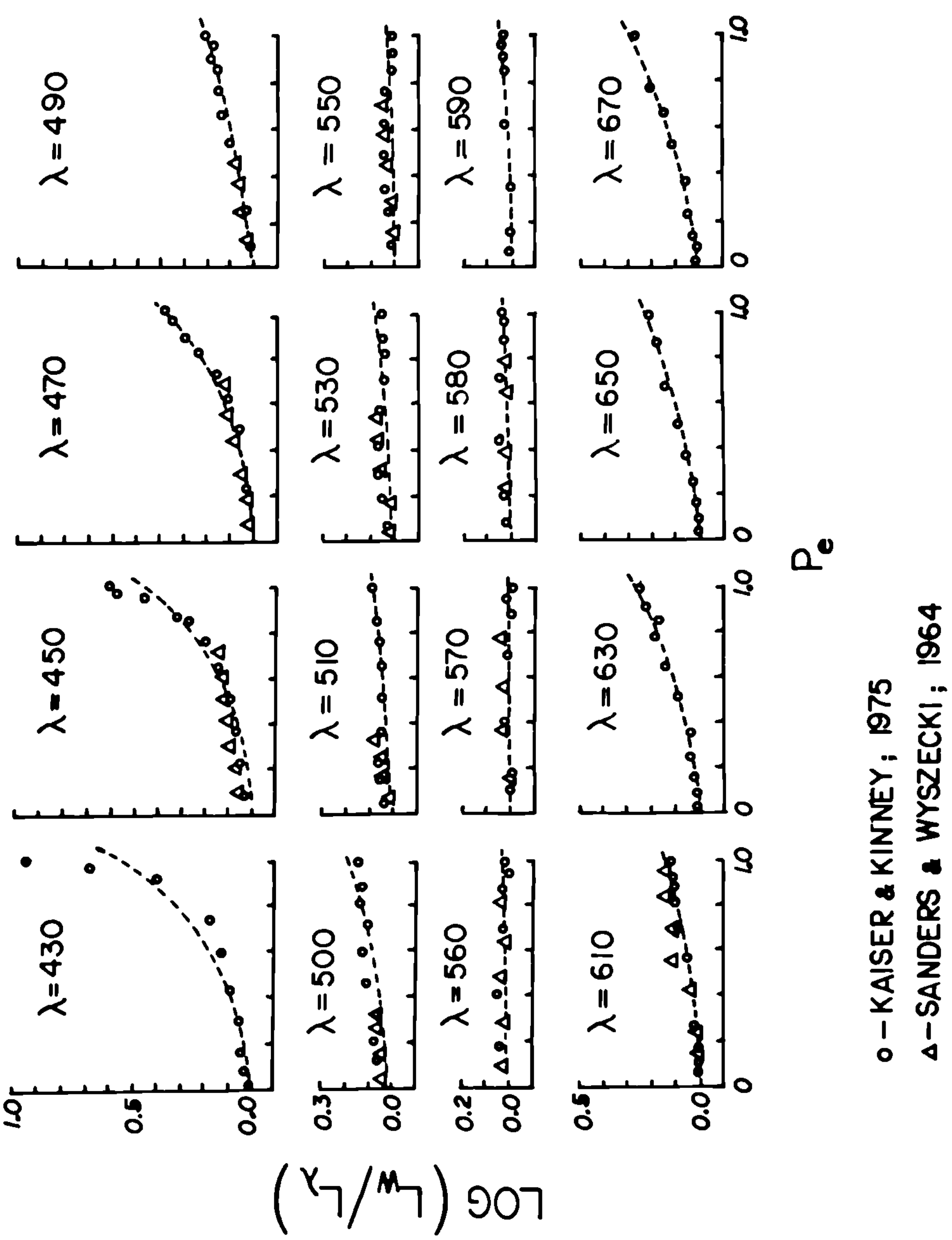
Helmholtz-Kohlrausch Effect Functions

($y = ax^b$)

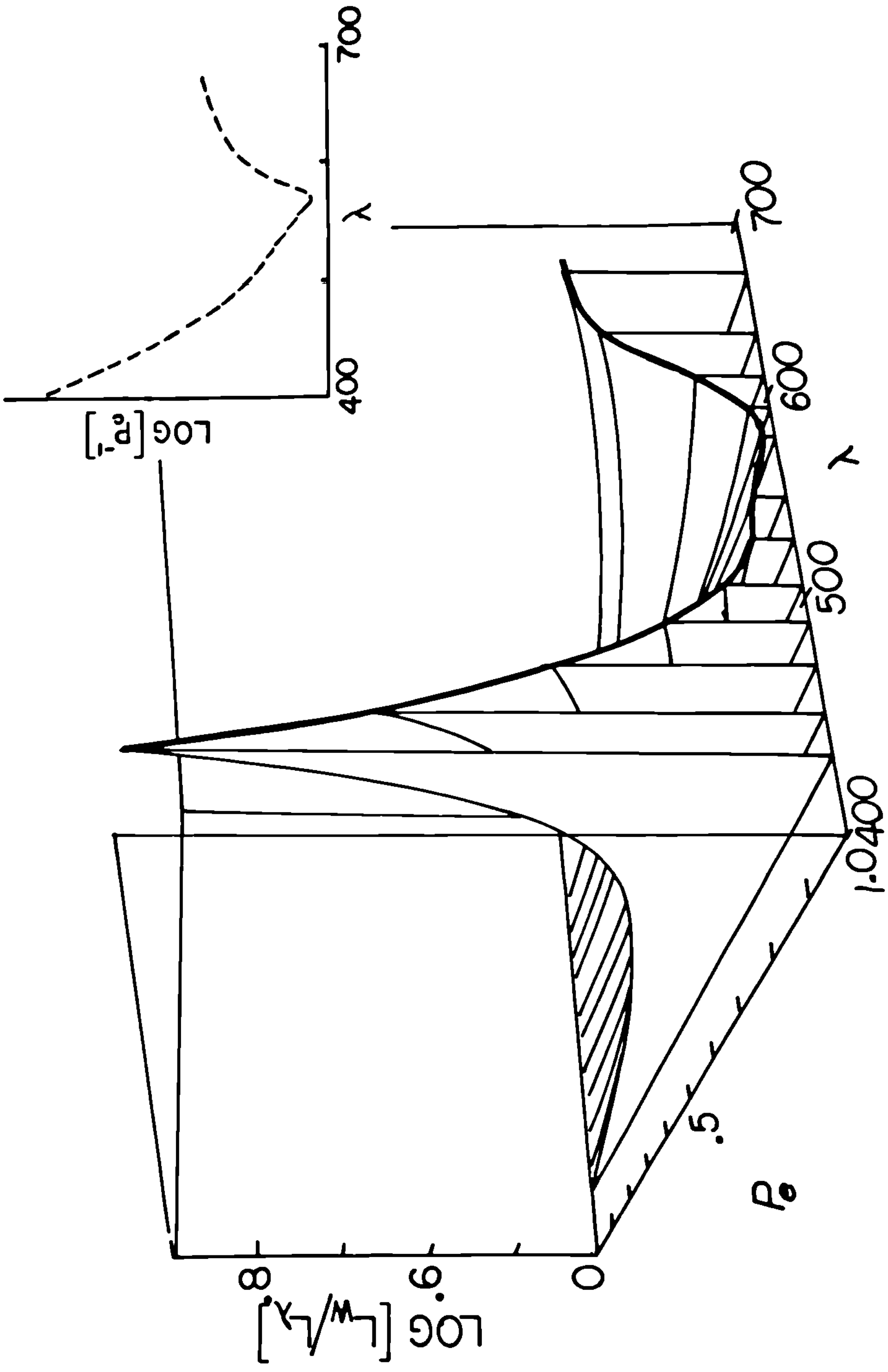
Wavelength (nm)	a	b	r^2
430	0.483	1.906	0.869
450	0.403	1.783	0.915
470	0.312	1.798	0.979
490	0.201	1.407	0.997
500	0.175	1.674	0.972
510	0.076	1.345	0.960
530	0.062	0.895	0.657
550	0.058	1.008	0.890
560	0.019	0.814	0.983
570	0.011	1.008	0.977
580	0.031	1.518	0.964
590	0.055	1.322	0.939
610	0.116	1.594	0.967
630	0.291	2.043	0.996
650	0.216	1.430	0.998
670	0.310	1.654	0.992

- -

Those same functions are plotted in a different manner in Figure 47 where all three dimensions of


λ=430
λ=450
λ=470
λ=490
λ=500
λ=510
λ=530
λ=550
λ=560
λ=570
λ=580
λ=590
λ=610
λ=630
λ=650
λ=670
LOG (L_W/L_λ)
P_e
o – KAISER & KINNEY; 1975
Δ – SANDERS & WYSZECKI; 1964

Figur 46



LOG [L_W/L_λ]
0
.6
.8
P_o
.5
1.0
400
500
600
700
λ
LOG [P_o^{-1}]
400
700
λ

Figure 47

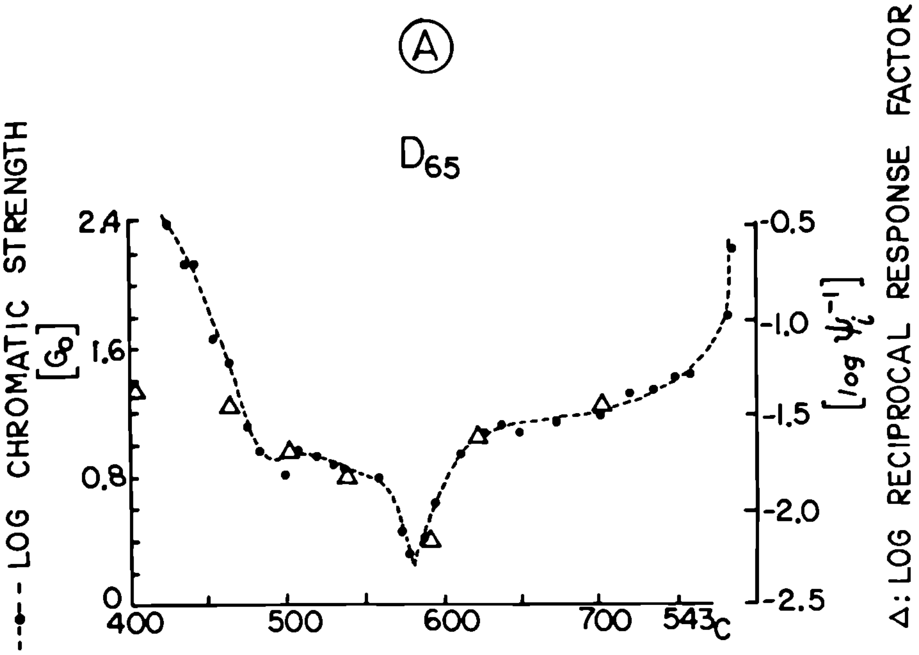
variation are shown. The relative luminance ratio required for equating brightnesses of chromatic samples and achromatic samples is seen to increase from near zero to higher values that depend on wavelength. The generic spectral shape of that dependency is displayed on the plane of unit purity versus wavelength. That shape is much the same as the chromatic purity function (shown in the inset for comparison). But the interesting aspect of Figure 47 is that the compression of the Helmholtz-Kohlrausch curves over planes of decreasing purity is much the same as the compression of experimentally determined purity functions found here for decreasing levels of saturation, with the important difference that the direction of compression is reversed. The purity functions for constant saturation are most steep near the white reference point. The luminance ratio functions of Figure 47 are most steep near the spectrum (i.e., at unit purity). That inverse relation might be interpreted as resulting from a single factor: chromatic stimuli are more effective response-modulators than are achromatic stimuli. Regardless of whether this occurs because of the complex nature of brightness or for other reasons, the result is that it takes less luminance to evoke a given brightness for chromatic stimuli. It also takes less change in colorimetric purity to evoke a given saturation increment for chromatic stimuli. Conversely, it could be said that a given change in luminance and purity lead to larger differences in brightness and saturation for chromatic stimuli than for achromatic ones.

Psychophysical functions for brightness and saturation behave in similar ways. Both mimic wavelength-dependencies that can be derived from relations among fundamental sensitivities. In studies of saturation, the two have often been confused by observers or results confounded by experimenters. This has led, in some instances, to a proliferation of what have been claimed to be 'independent dimensions' of color appearance when, apparently, only attributes consisting of combinations of dimensions (as defined by Titchner) have been involved. Evans' (1974)[93] claim for 'chromatic strength' as an independent dimension appears to be one such instance.

Chromatic strength has been defined by Evans (1974, p.111)[93] as the antilog of G_o; where G_o is a difference in log luminances of focal and surround stimuli when the sample appears to just-not-contain any trace of gray. The chromatic strength of any stimulus is determined by a relationship involving colorimetric purity and strength of the spectral stimulus of the same dominant wavelength. 'Brilliance' is defined as a sum of chromatic strengths and luminances; it is simply a term used to include both the appearance of grayness and what has been called 'fluorence' (i.e., luminous-appearing surface colors). It is, then, chromatic strength in which resides any claim for separate and independent dimensionality.

In Figure 40b (page 181) we saw that for the observers of this experiment, luminance differences among white and maximum lightness chromatic stimuli, there was a simple power relation with G_o; the logarithms of chromatic strength. Hence, chromatic strength is related to lightness. But the experimental data of this study show another relationship with G_o as well. Figure 48 illustrates that relationship.

The graph at the top of that figure shows log chromatic strength (G_o) plotted against wavelength. The data were taken from Evans and Swenholt (1969)[96] and are shown here as solid circles. The dashed curve is the same as those authors drew through the same data points. In addition, Figure 48a includes several points represented as open triangles. Those points are derived from psychophysical functions of saturation versus colorimetric purity as scaled by observers in this work. Such functions may be expressed as either stimulus-corrected or response-corrected power functions. In this case, response-corrected functions with constant exponent of 1/3 were computed. The response increments of those equations form the basis for the triangular points shown in Figure 48a. The points are actually


Ⓐ
D65
LOG CHROMATIC STRENGTH [G0]
Δ: LOG RECIPROCAL RESPONSE FACTOR [log ψi⁻¹]
2.4
1.6
0.8
0
400
500
600
700
543C
-0.5
-1.0
-1.5
-2.0
-2.5

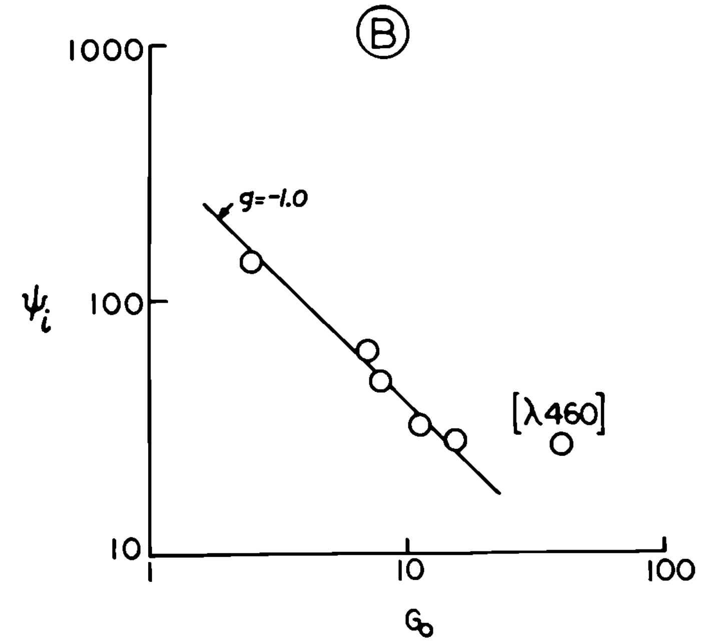
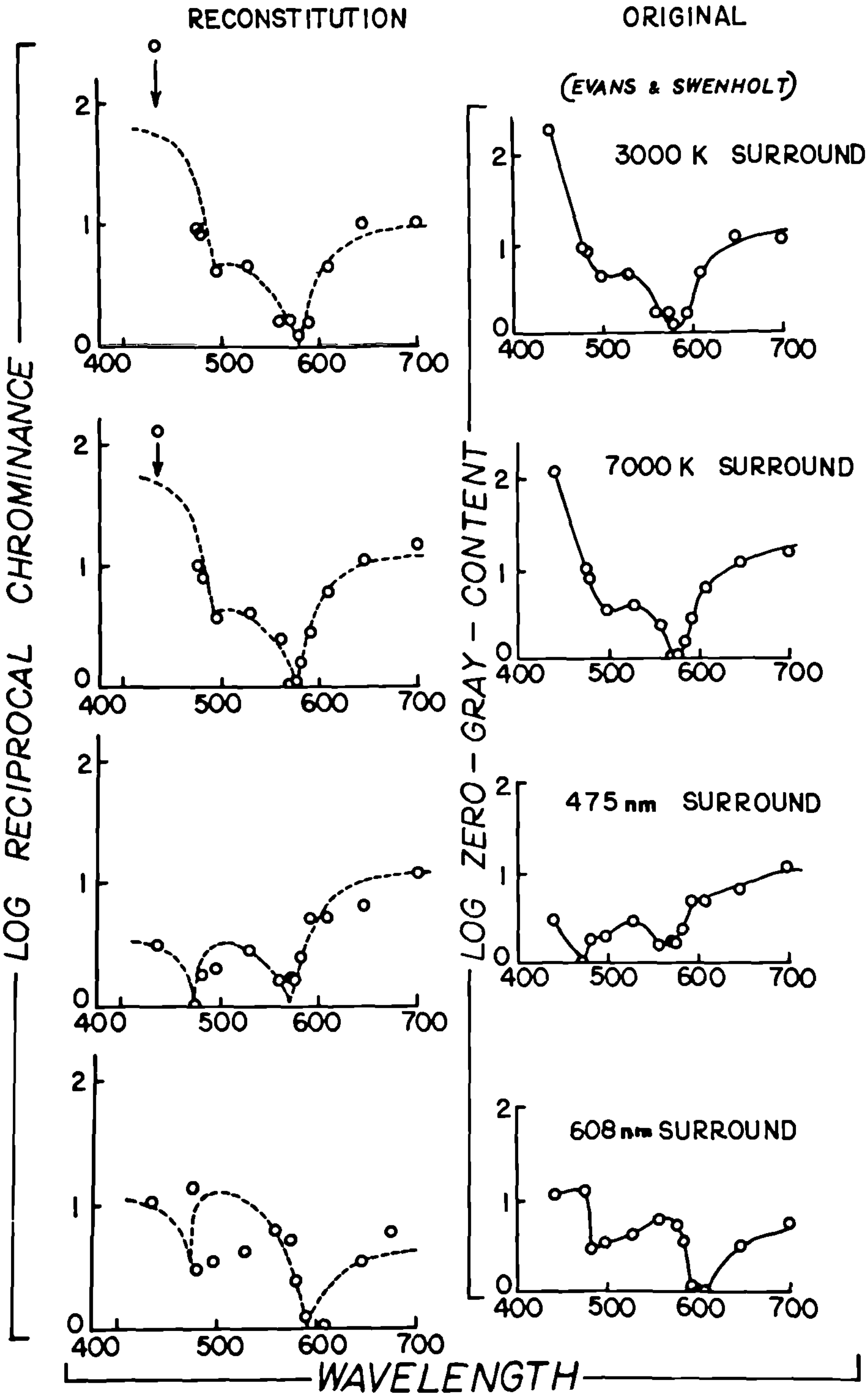

Ⓑ
1000
100
10
ψi
g=-1.0
[λ460]
1
10
100
G0

Figure 48

the logarithms of the reciprocals of response increments.

In general, the triangles are coincident with the dashed log chromatic strength function. Figure 48b makes this last point more explicitly. Except for the shortest wavelengths, that relation is described by a line of slope -1. Hence, chromatic strength is related to saturation (colorfulness). But we have already seen that chromatic strength is related to lightness as well. Thus, it is a complex, dependent rather than independent attribute of color appearance. Looked at this way, gray content, brilliance, and chromatic strength may simply be taken as other ways of expressing the same color appearance phenomena that have been studied in this research where results have been reported as more conventional attribute-combinations.

Evans and Swenholt (1967,1968,1969)[94-96] reported a series of studies in which they determined chromatic strength or zero gray content. In one of those reports (Evans and Swenholt 1969)[96], a series of chromatic- and achromatic-appearing surrounds was used. The surrounds tended to control the observer's adaptation. Two neutral surrounds involved correlated color temperatures of 7,000 K and 3,000 K; not greatly different from the D_{65} and A conditions used in this experiment. Three chromatic surrounds were provided by illumination through interference filters with spectral centroids of 475 nm, 528 nm, and 608 nm. In all five cases, contours of G_o versus wavelength were determined by experiment. Graphs illustrating all but the 528 nm condition are shown on the right of Figure 49; in the column labeled 'original'. The data points (circles) and curves drawn through them are as published by Evans and Swenholt. The notable aspect of those curves is that the wavelength at which G_o is minimum varies with adaptation. In addition, the shapes of the curves differ with adaptation; particularly for the highly chromatic conditions. The wavelength of minimum G_o for adaptation to 475 nm and 608 nm surrounds - as well as for the 528 nm surround which is not shown - tends to be the same as the dominant wavelength of the surround. In the case of the achromatic-



RECONSTITUTION
ORIGINAL
(EVANS & SWENHOLT)
3000 K SURROUND
7000 K SURROUND
475 nm SURROUND
608 nm SURROUND
LOG RECIPROCAL CHROMINANCE
LOG ZERO-GRAY-CONTENT
WAVELENGTH

Figure 49

appearing surrounds (7,000 K and 3,000 K), the minimum G_o is at a higher dominant wavelength for the lower color temperature surround.

These changes in the shapes and minima of the threshold gray-content functions seem to imply an underlying system in the chromatic response functions. The curves drawn by Evans and Swenholt to fit their data points resemble a trimodal mixture curve. Also, the curve published by Evans and Swenholt for a proportionality constant of chromatic moments expressed in terms of G_o over dominant wavelength is a trimodal function with minima just below 500 nm and 600 nm. Interestingly, those are the same wavelength regions where the relative minima or inflection points for G_o occur. Examination of the chrominance curve in Figure 42c (page 187) indicates inflection points in these same regions. In fact, the logarithms of the reciprocals of chrominance yields a trimodal function; as if it were composed of three parts. The relative heights of those parts would depend upon the multiplicative and additive factors that might be associated with the chromatic response curves (C_1 and C_2 in Figure 42b). By varying the heights independently, it is possible to generate a variety of curve-shapes with respect to dominant wavelength. That has been done for the graphs on the left side of Figure 49 (the column labeled 'reconstitution'). The dashed curves were constructed by varying the heights, in logarithmic coordinates, of the log reciprocal chrominance components in order to make a visual fit to the original data points of Evans and Swenholt. In general, the fit is fair.

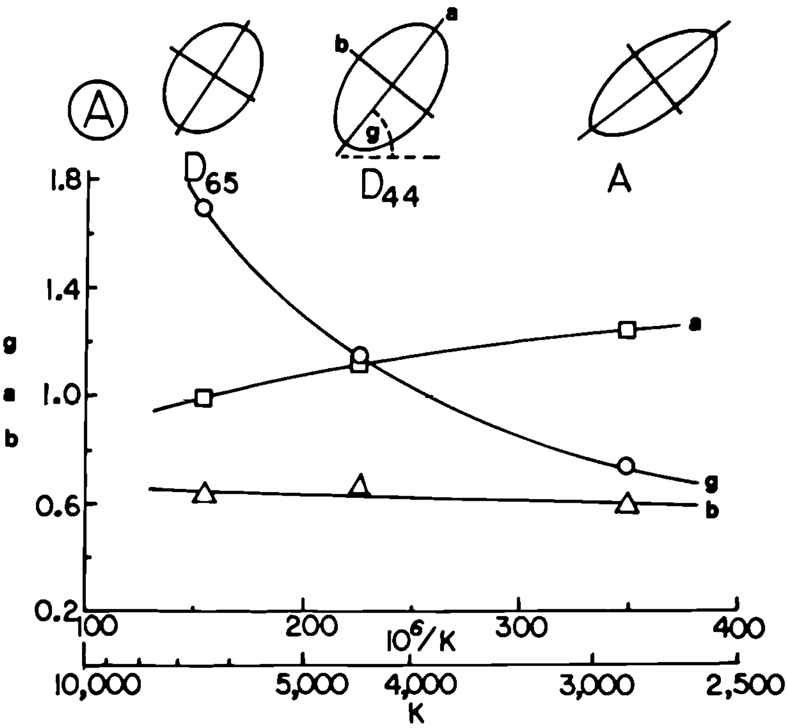
All of the foregoing interpretations, taken together, provide reasonably compelling evidence that saturation varies in systematic and likely predictable ways with chromatic adaptation. This seems to be the case both for threshold and suprathreshold purities. It would appear that careful study of the factors affecting the shapes of the chromatic purity functions should offer a novel and useful way to study chromatic adaptation. Analysis of this kind may yield valuable clues to the nature of the visual mechanism for chromatic adaptation. Such an approach would be an alternative to the classical method of determining adaptational metamers. It addresses the coded neural stage of visual processing rather than complex sensitivities. Since the adaptive process appears to be nonlinear, what is now required is more information on the ways in which chromatic opponent responses change with adaptation.

Systematic variations

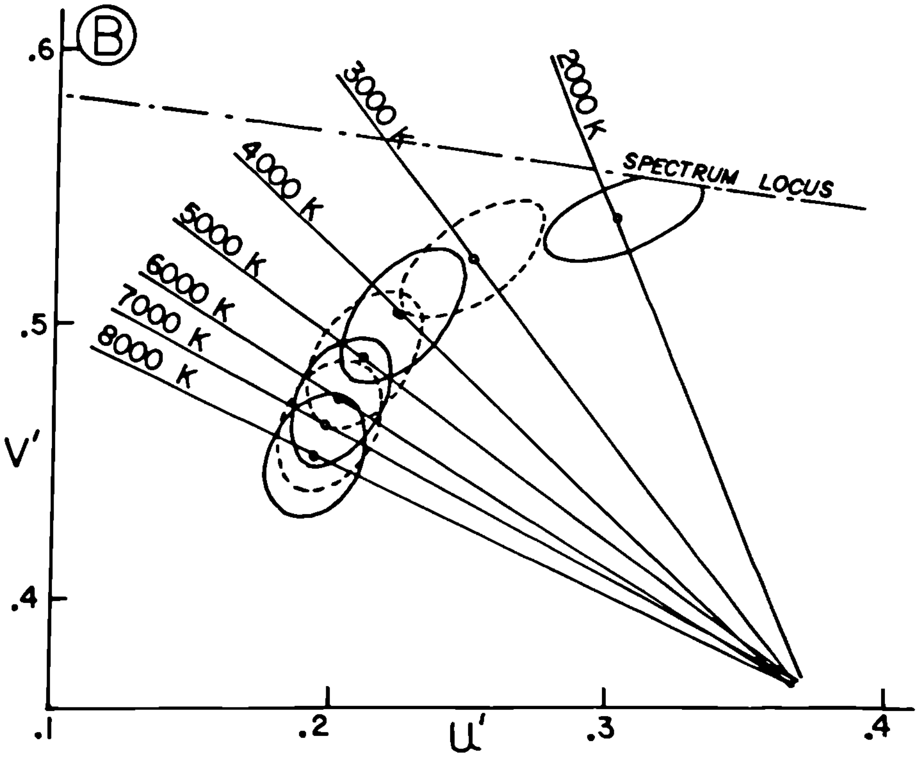
The low saturation (20) contours of Figures 13, 14, and 15 (on pages 130 to 132) resemble ellipses in shape. They may be approximated with ellipses to determine what, if any, systematic changes in shapes and orientations may occur with variations in chromaticity of adapting illuminants. Figure 50 has been prepared to do this.

In Figure 50a the ellipses that, on average, fit saturation 20 contours for each of the three adaptations have been specified in terms of their major and minor axes and slopes of the major axes in the CIE 1976 u',v' chromaticity diagram. Those parameter values are plotted against reciprocal megakelvins. The graph shows that the major axis tends to increase and the minor axis decreases slightly with increasing mired value; i.e., as color temperature of adaptation decreases. In addition, the slope of the major axis decreases as color temperature declines.

Those relationships were used to construct the series of contours shown in Figure 50b. Ellipses based on the model relationship were constructed for adapting chromaticities along the daylight and Planckian loci; corresponding to color temperatures from 2,000 K to 8,000 K. In the process of constructing the graph, another interesting feature of the ellipses was uncovered. The minor axes all tend to intersect at a common point. They have been extended in Figure 50b to illustrate this feature. The common point of intersection may, in itself, have little significance. It appears, rather, to be a concomitant of another, perhaps more signifi-



A
D65
D44
A
a
b
g
1.8
1.4
1.0
0.6
0.2
g
a
b
100
200
300
400
10^6/K
10,000
5,000
4,000
3,000
2,500
K



B
.6
.5
.4
V'
.1
.2
.3
.4
U'
3000 K
2000 K
4000 K
5000 K
6000 K
7000 K
8000 K
SPECTRUM LOCUS

igure 50

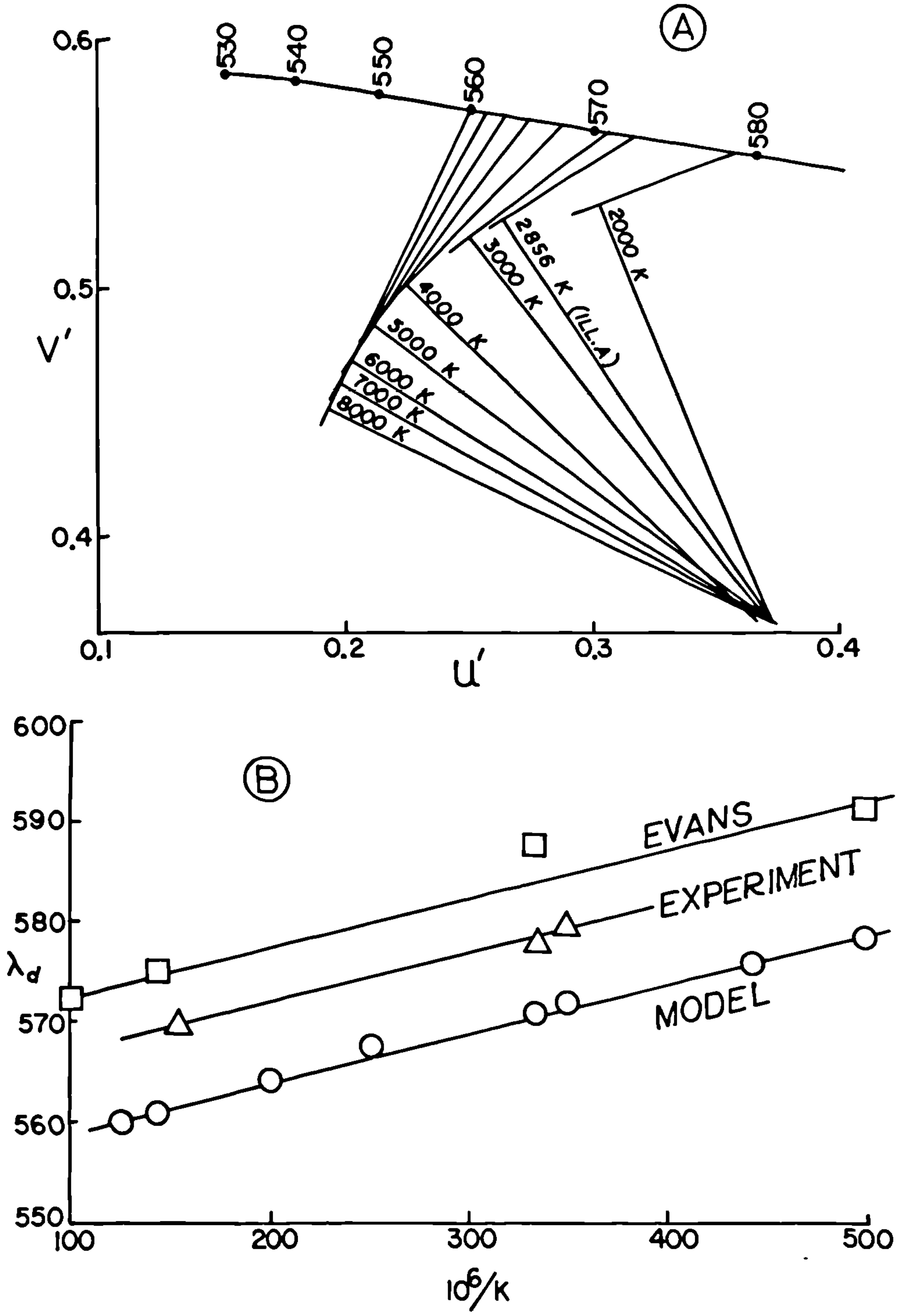

A
530
540
550
560
570
580
0.6
0.5
0.4
V′
2856 K (ILL.A)
3000 K
2000 K
4000 K
5000 K
6000 K
7000 K
8000 K
0.1
0.2
0.3
0.4
u′
B
600
590
580
570
560
550
λ_d
EVANS
EXPERIMENT
MODEL
100
200
300
400
500
$10^6/K$

Figure 51

cant, systematic aspect of the shift in contours with changing chromatic adaptation. That is a phenomenon first noted by Evans.

In summarizing his and Swenholt's work on chromatic strength, Evans (1974, pp.138-139)[93] called attention to a similar feature found in their results: "A curious fact, incidentally, and one of no significance that I can see, was encountered in our study of surrounds of different color temperatures from 2000 to 10,000 K. If on the CIE chromaticity diagram the wavelength on the spectrum locus corresponding to our G_o minimum is connected to the point on the blackbody locus corresponding to the color temperature of the surround, these lines are approximately all tangent to the blackbody locus! In other words the monochromatic wavelength having most nearly the same brilliance as a surround of a given color temperature can be estimated by extending the tangent from that point of the color temperature locus to the spectrum locus." The shape of the Planckian locus is such that the lines tangent to the chromaticity points for illuminants of decreasing color temperature would intersect the spectrum locus at systematically increasing wavelengths. Thus, dominant wavelengths corresponding to G_o increase with decreasing color temperature; at least for Planckian and daylight radiators. We have already seen that the G_o minima correspond closely to the minima for chromatic purity functions. Accordingly, we may say that Evans and Swenholt found that chromatic purity minima shifted upward in wavelength as the color temperature of adapting illumination decreased.

Now, if we examine the major, rather than the minor axes of the model ellipses in Figure 50, we find that a similar prediction results from this model. The major axes are, of course, perpendicular to the minor axes. When they are constructed and extended to the spectrum locus (as in Figure 51a) they also intersect so as to yield higher and higher wavelengths with decreasing color temperature. Further, these major axes also turn out to be essentially tangent to the Planckian locus. This is a strong suggestion of fundamental agreement between results of two very different experimental approaches to the study of chromatic adaptation.

Figure 51b compares the Evans-Swenholt results with experimental results obtained here and with the predictions of the rather simplistic ellipse-model of Figure 50. That graph shows dominant wavelength of the parameter in question as a function of reciprocal megakelvins. Data points shown as squares are the wavelengths and mireds reported by Evans (1974, p.132)[93]: 2,000 K = 592 nm, 3,000 K = 588 nm, 7,000 K = 575 nm, and 10,000 K = 572 nm. The three triangular points are for the illuminant conditions used in the present study. Finally, the eight circular points are predictions of the model in Figure 51a. In the case of the squares, the wavelengths are the ones at which G_o is minimum. For the triangles, wavelength position on the graph corresponds to the dominant wavelength of minimum chromatic purity at a saturation of 20. The wavelength at which the major axis of the model ellipse intersects the spectrum locus is used as ordinate value for the circles.

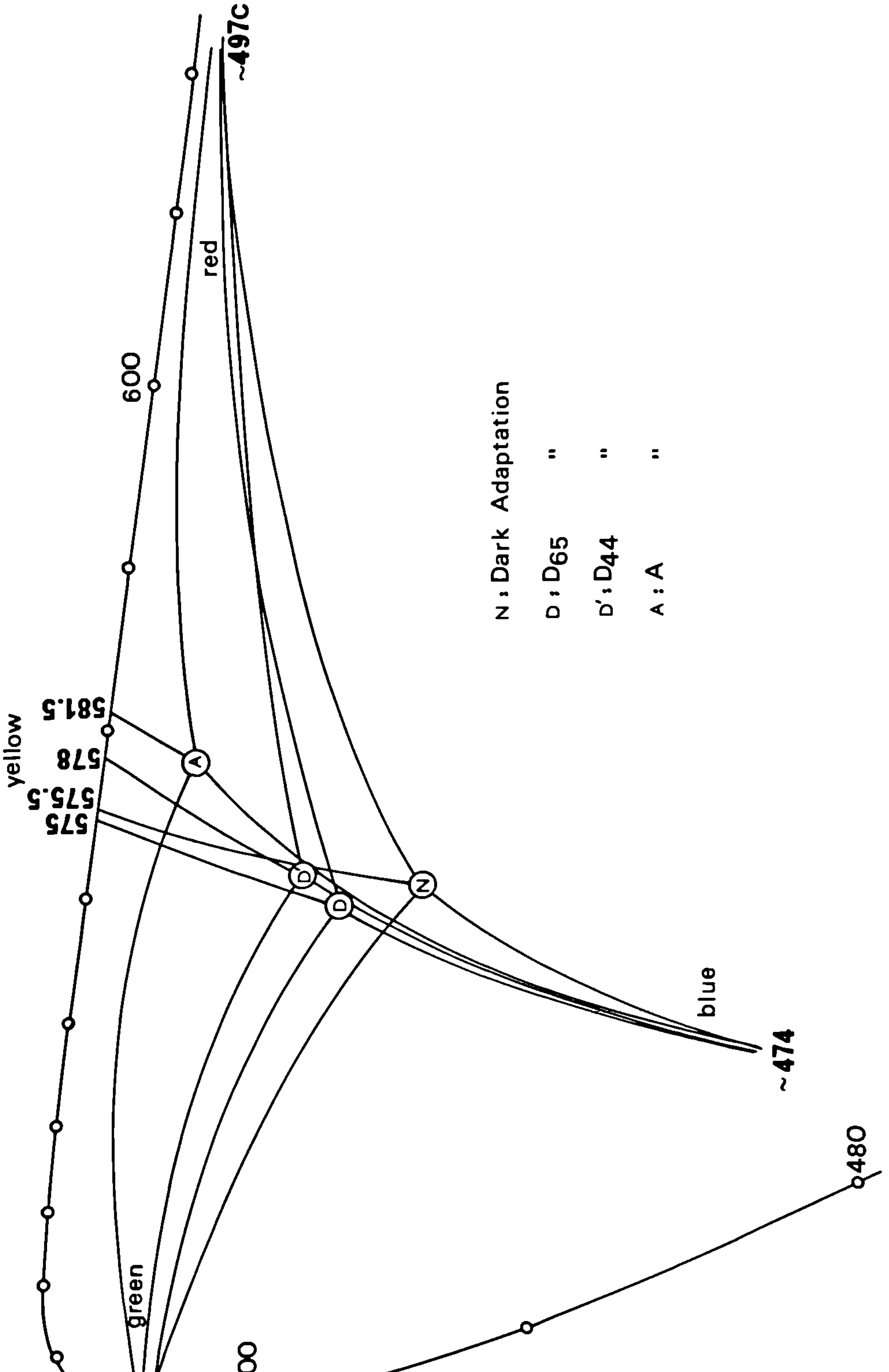
There is an astonishing similarity among the data shown in Figure 51b. Not only do all the functions form straight lines, but they all have the same slope! The common slope of wavelength in nanometers versus mireds is 0.05. The intercept value for Evans' data is 567. For the experimental results presented here (not the ellipse-model) the intercept is 565. An average function based on what are, apparently, the only two existing determinations of this relationship would then be: $y = 0.05x + 566$; where y is nanometers and x is mireds.

Clearly, there is a common feature in these data that implies systematic variation as a consequence of changes in chromatic adaptation. The minimum of the chromatic purity function shifts systematically upward in wavelength as correlated color temperature of adapting illumination decreases. Two very different experimental studies indicate that this shift is linear with mireds at a gradient of 0.05. Any model of chromatic adaptation will have to reflect that shift. Since it is a shift of the minimum point on the chromatic purity function which may be determined from chromatic response values, that means that any adaptation model must provide for appropriate changes in opponent chromatic response functions, not merely proportionate variations in fundamental sensitivities. The weight of evidence seems to indicate that simple proportionate variations (i.e., linear coefficient rules) cannot yield the kinds of shifts described here and also account for all the other features observed in color appearance changes as chromatic adaptation is varied.

Invariances

Thus far, emphasis has been on systematic variations. There is also a singular invariance to be seen in the experimental data presented here. That is the striking tendency for the wavelengths at which three of the four unitary hue loci intersect the spectrum locus (or 'purple boundary') to remain the same regardless of the condition of adaptation.

Figure 52 illustrates this finding. The coordinates of that figure are CIE 1976 u',v'. Red, green, blue and yellow unitary hue loci are plotted for each of the four adaptation conditions studied in which the stimuli were at 200 $cd \cdot m^{-2}$. Neutral points labeled D and D' correspond to D_{65} and D_{44} adaptations, respectively. Point A is for A adaptation and N is for the dark surround condition. As we have seen in the foregoing paragraphs, dominant wavelengths for yellow unitary hue - which are approximately the same as the chromatic purity minima - vary with adaptation. However, those for red, green and blue tend to converge on each of three wavelengths in the limiting case. Blue hue loci converge on a spectral wavelength of about 474 nm. Green goes to about 508 nm. Red has a common limit-point of about 497c nm (i.e., a complementary wavelength with respect to Illuminant E). Those are the wavelengths at which the three extrapolated unitary hue loci intersect the spectral or aspectral boundaries of the chromaticity diagram for all four quite different conditions of chromatic adaptation.


N : Dark Adaptation
D : D65 "
D' : D44 "
A : A "
~497C
red
600
yellow
581.5
578
575.5
575
blue
~474
480
green
500
~508

igure 52

It is of interest to compare these values with those reported by other workers who have measured the wavelengths at which unitary red, green, and blue hues are perceived by observers. Judd (1951)[187] and Dimmick and Hubbard (1939a,b)[79,80] have summarized the results of a number of such studies. Most of them were conducted with dark surrounds. But we see from Figure 52 that the dark surround results are the same as with light surrounds, so a comparison should be reasonably valid. Table XXIII lists the data published by Judd (1951).

Table XXIII

Wavelengths for Unitary Hues - Prior Work

Experimenter	Date	Red	Green	Blue
Bezold	1874	656-760	532	468
Donders	1884	-	535	485
Hess	1888	-	495	471
Rood	1890	700	527	473
Hering	1898	-	505	470
Voeste	1898	-	505	470
von Kries	1907	-	503	-
Westphal	1909	-	506	479
Dreher	1911	-	509	477
Ridgway	1912	644	520	473
Goldytsch	1916	-	-	468
Bradley	1920	656	514	469
Goldmann	1922	-	504	468
Priest	1926	680	515	475
Brückner	1927	-	498	471
Schubert	1928	-	500	467
Purdy	1931	-	506	474
Ornstein et al	1934	630	528	487
Verbeek et al	1935	-	530	-
Schouten	1935	-	512	472
Dimmick & Hubbard	1939	495c	515	475
(Approximate arithmetic average)	:	495c	513	473
Theoretical Data				
Hering		498.2c	498.2	477.0
Ladd-Franklin		495.7c	510.6	468.9
von Kries & Schrödinger		495.7c	495.7	468.9
Müller		498.2c	498.2	477.0

The theoretical predictions at the bottom of Table XXIII mostly indicate, for various reasons, that red and green unitary hues lie at identical but complementary wavelengths. The data from practical experiments, however, do not show such a simple relationship. The averages are close to but not quite identical complementaries.

The similarity of those average values to the experimental results illustrated in Figure 52 is striking. Certainly the data derived here are well within the range found by others. But it is interesting that the quite different experimental technique used in this research yields results that are so similar to the average values for spectral wavelengths of the three unitary hues found by other experimenters. Table XXIV compares them.

Table XXIV

Wavlengths for R,G,B Unitary Hues

Hue	Average of Other Experiments	Present Work
Blue	473	474
Green	513	508
Red	495c	497c

Perhaps more important than the similarities set forth in Table XXIV, is the result that these wavelengths corresponding to these unitary hues at maximum saturation are invariant over chromatic adaptation. Whether such a finding would obtain with adaptation to other more highly chromatic illuminants is not known with certainty, but does appear doubtful (Cicerone, Krantz and Larimer 1975)[66]. When adaptation to spectral stimuli has been used, only one unitary is found to be invariant in wavelength. However, with the normally encountered range of illuminant-chromaticity included in this research, the invariance of the three unitary hue maxima does seem to hold as a first-order approximation.

To the extent that this finding correctly represents the underlying facts, it provides another form of evidence against the coefficient law. Recall that von Kries said: "If we set the condition that three definite points of the color chart are to be invariable, and if we, for those points, fix the effect of the adaptation as an apparent change of quantity by a coefficient, thereby the whole system of adaptation-shifts is determined in such a manner that no other points can remain unshifted" (q.v., MacAdam 1970)[235]. Thus, the linear model postulates that only the chromaticities of the three fundamental primaries remain invariant. But the results of this work suggest that three other points remain invariant over changes in adaptation of the kind studied here. They cannot be the same points. Ergo, the present finding militates against linear transform theory.

This matter of invariance of wavelengths for unitary hues at maximum saturation is an important one in considering physiological sources and sites for chromatic adaptation. If adaptation is determined simply by ratios of photoreceptor quantum catches to set the gains of a trichromatic system, then we would expect no invariances with adaptation. With a purely additive model, we would expect that with adaptation to <u>either</u> blue or yellow unitary light, <u>both</u> blue and yellow hues would be associated with invariant wavelengths, and the same analogy would hold for adaptation to either red or green unitary light (Cicerone, Krantz and Larimer 1975)[66]. But a group of workers from the University of Michigan and Temple University (v., Larimer, Krantz and Cicerone 1974,1975; Cicerone, Krantz and Larimer 1975)[223,224,66] found in their studies of adaptation to monochromatic lights which yielded unitary hues under dark adaptation, that only the wavelength of the adapting unitary hue remained invariant. Other equilibrium wavelengths - wavelengths for unitary hues associated with the opponent-chromatic process not involving the unitary used for adaptation - tended to shift toward the wavelength of adaptation. However, that finding was for quite low levels of adaptation illumination; less than 500 down to 40 trolands. At higher levels, up to about 4,000 trolands, both invariance and coefficient relationships broke down. It is difficult to relate this work directly to experimental results such as those of the research described here because we do not know the nature of any functional relationship between the equality-of-response criteria used in the equilibrium experiments and the magnitudes of perception scaled by observers in this work. It is probably reasonable to rule out a simple one-to-one correspondence. None-the-less, both the equilibrium results and the invariance found here imply that the chromatic adaptation process does not obey a simple coefficient rule and neither is a simple induction transform adequate. It is most likely some combination of both, with component nonlinearities involved as well. The nature of the transform apparently does change from quite low levels of stimulation to normally high ones, as Hunt (1950)[153] has suggested. But the findings that brightness and saturation change much more than hue (if hue does change at all) within the normal photopic range of illumination, seems to point to a reasonably stable form for adaptation transformation for that range of stimulation. Although stable, it need not be (and apparently is not) linear.

Relative and absolute saturation

Differences in experimental methodology as well as differences in stimulus conditions can lead to quite large discrepancies among the results of experiments. Even for similar stimulus conditions and methodologies, subtle distinctions between scaling criteria can lead to diametrically opposed conclusions based on equally valid data. This is perhaps most obvious in magnitude estimation results for scaling saturation.

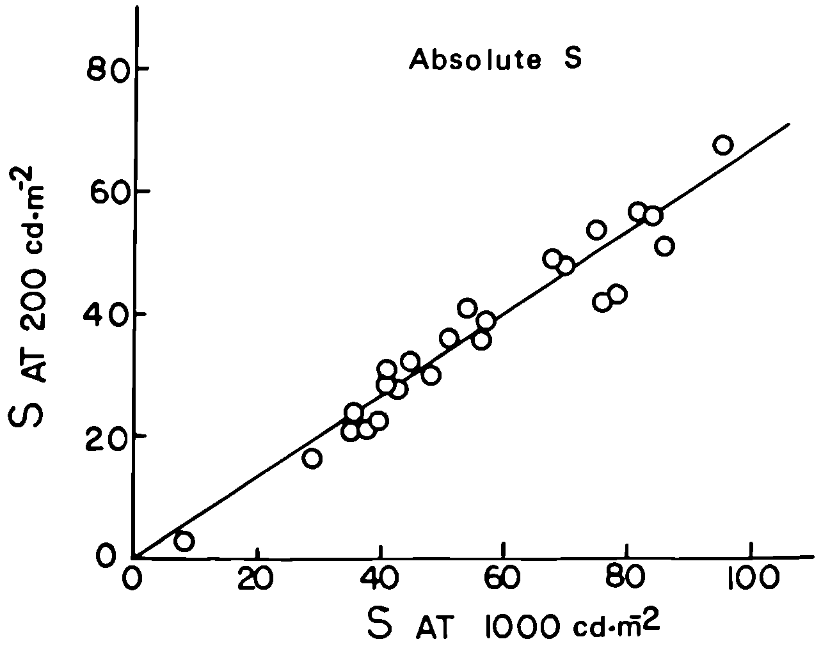
Sobagaki, Takahama, Yamanaka, Nishimoto and Nayatani (1975)[306] carried out an extensive series of magnitude estimation experiments designed to study chromatic adaptation. In subsequent experiments (Sobagaki, Takahama and Nayatani 1975a)[307] they examined the question of whether or not the nature of instructions to observers influenced results for scaling saturation. Three saturation paradigms were used. Two of these could be called relative saturation methods and one was roughly equivalent to the absolute method used in this work.

When the original relative saturation data were plotted against the other two sets of results (one relative and one absolute), the relative results were virtually identical but the absolute data formed a nonlinear relation; although the authors concluded that there was little difference among the methods. In fact, method didn't make much difference in determining chromaticities that elicited equal color appearances under adaptation to CIE Illuminant A for the 8 samples of the CIE Colour Rendering Method. But the methods may have significantly influenced the results of still another experiment these workers conducted.

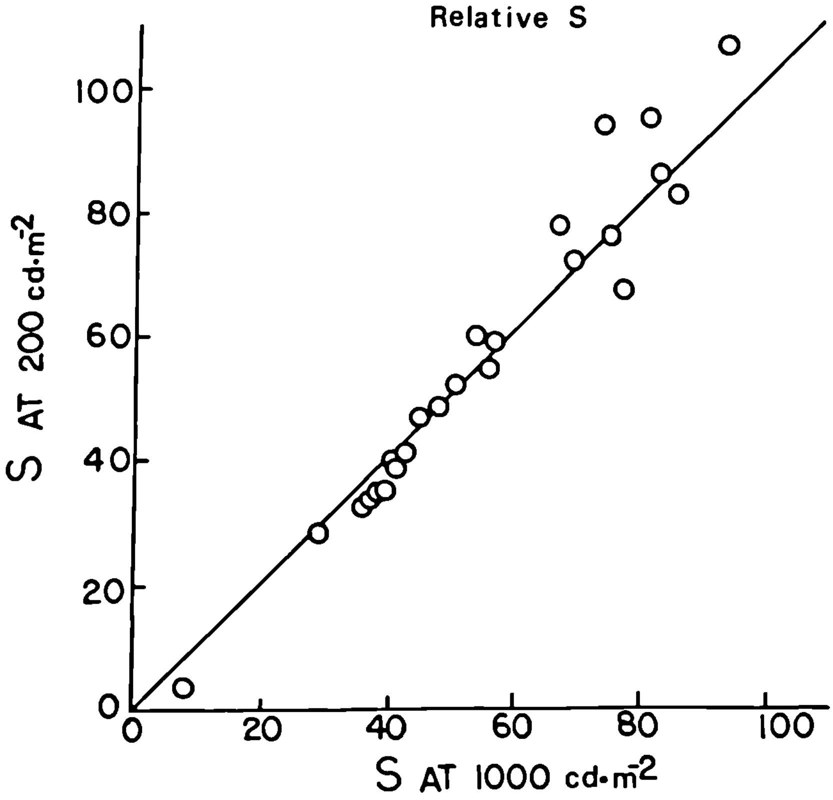
They also studied the effect of illuminance on saturation (Sobagaki, Takaham and Nayatani 1975b)[308]. Observers scaled saturation according to the original relative paradigm for samples illuminated with 100, 1,000 and 10,000 lux. All the results were related by a linear function of unit slope. In other words, saturation, as scaled, did not change with illuminance. The authors noted that they had expected to find a different result based on the work of Hunt (1950)[153]. But their data clearly showed saturation to be independent of illuminance.

A distinction has been made here between absolute and relative attributes of color appearance. The main body of experimental data in this study involved scaling absolute saturation. The results show a distinct level-dependence. Absolute saturation varies roughly as the one-fourth power of illuminance. Accordingly, the present results appear to be at variance with those of Sobagaki et al.

To examine this question further, a subgroup of three observers (A,B and E) scaled all stimuli under two conditions of D_{65} illuminance: yielding surround luminances of 1,000 and 200 $cd \cdot m^{-2}$. The absolute saturation results are shown at the top of Figure 53. Saturation of Value 5 samples at the two illuminances are linearly related. But the slope of the relation for the 200 $cd \cdot m^{-2}$ surround condition against the 1,000 $cd \cdot m^{-2}$ one is less than unity; just under 0.7, in fact.



Absolute S
S AT 200 cd·m^{-2}
S AT 1000 cd·m^{-2}
0
20
40
60
80
100



Relative S
S AT 200 cd·m^{-2}
S AT 1000 cd·m^{-2}
0
20
40
60
80
100

Figure 53

On the other hand, the same observers also scaled relative saturation of the same samples at both illuminance conditions and produced quite different results. Relative saturation was defined in the same way as absolute saturation <u>except</u> that a modulus of 100 was assigned to an appearance of zero gray content. Thus, relative saturation was a proportion of relative chromatic content. The relationship to colorimetric purity was, then, effectively normalized for every wavelength. The results of that experiment are shown in the bottom graph of Figure 53. Now the linear relation between saturations at the two illuminances has a slope of unity; the same result found by Sobagaki and co-workers when they scaled saturation as a relative attribute.

There is no difference between the Sobagaki et al results and the results of this work <u>when the same attributes are scaled</u>. As those workers showed, the particular saturation attribute used makes little difference if one is merely interested in determining adaptational metamers. However, the results of this research show that the choice of saturation attribute makes a great deal of difference to the inferences that are drawn regarding the influence of illuminance on color appearance. By its very nature, relative saturation remains virtually constant over illuminance. This is very likely one of the reasons why color image reproduction in photography, printing and televisions works as well as it does. On the other hand, absolute saturation is decidedly dependent on illuminance. In any situation where an observer is interested in absolute colorfulness, he will attend to absolute saturation and it would be a mistake to assume - from relative data - that he will see no saturation differences when illuminance varies. Just as it would be a mistake to assume that brightness (an absolute attribute) does not change with illuminance merely because lightness (a relative attribute) is found to be nearly constant over a broad range of illuminances. The two kinds of attributes may take on different importances depending upon the observing situation and ulterior matters of practical interest.

Comparisons with prior work

It should be clear from the foregoing discussion that the data obtained in this research can be expressed in a variety of ways. In addition to showing directly the psychosensorial relations among attributes of color appearance as adaptation changes, the data may be arranged for comparison with various psychophysical expressions and sensory physical contours of perceptual constancy. A set of sensory physical contours of particular interest is that which displays predicted iso-appearance loci under one or more conditions of chromatic adaptation. These can be specified as chromaticity coordinates corresponding to equal color appearances under various illuminants.

Appendix M lists CIE 1976 u',v' chromaticities for 8 hues at several levels of saturation under each of 4 adaptation conditions: D_{65}, D_{44}, A and dark adaptation. The first three are for samples with luminance factors of 0.20 (approximately Munsell Value 5) with respect to a 1,000 $cd \cdot m^{-2}$ surround. When plotted on the u',v' diagram, those data define maps of corresponding color appearances for the different adaptation conditions. Such maps may be compared with similar sensory physical maps predicted or determined by the work of other experimenters who have studied chromatic adaptation using surface color stimuli.

The maps need not be limited to samples of Value 5. The relationship illustrated in Figure 34 (on page 169) and Equation 18 (on page 168) provides a means for converting the data of Appendix M to any other level of Munsell Value (or luminance factor). It is possible, then, to compare the results of this work with those of other experimenters who used stimuli of different luminance factors. A comparison of that kind is made in Figure 54.

The graphs in that figure show interpolated predictions of u',v' chromaticities with respect to CIE Illuminant A for 8 hues at 3 saturations each. Work of Pointer and Ensell (1975)[270] is shown in Figure 54a. Results from Sobagaki, Takahama, Yamanaka, Nishimoto and Nayatani (1975)[306] are displayed in b. Data from the present research are set forth in c. The 8 hues chosen for illustration are the unitaries (red, green, blue, and yellow) and their intermediates (yellow-red, yellow-green, blue-green, and blue-red). Since those hues were scaled as hue proportions in all three experiments, the results should be directly comparable. Saturation scales in this research and that of Sobagaki et al had similar scale factors and, therefore, saturations of 20, 40, and 60 are plotted in 54b and 54c. The Pointer-Ensell saturation scale-factor was about 3/4 of that in the other two works and for that reason, saturations of 15, 30, and 45 are plotted in 54a. Accordingly, the saturation contours should all be directly comparable in Figure 54. Luminance factors for the data displayed are approximately equivalent to Munsell Values of 7.2 to 7.5; the Sobagaki et al luminance factor was 0.46 and the other two are 0.50.

The general shapes of the maps in 54a and 54c agree quite well. It is of interest to note that both experiments produced data that, under D_{65} adaptation, closely matched the contours of the Munsell Renotation map. The map based on work by Sobagaki et al has a different shape from the other two maps. The D_{65} map of the Sobagaki work did not match the Munsell map very closely.

All three experiments used magnitude estimation to determine color appearances of surface color stimuli over chromatic adaptation. Comparison of their results seems to indicate that there are two distinctly different kinds of results that may be obtained from such studies. Figure 55 allows a somewhat more direct examination of the nature of these differences. Saturation contours from all three works are superimposed in 55a. Unitary hue loci are superimposed in 55b.

The hue contours of the Pointer-Ensell work are quite similar to those of the present work. The Sobagaki et al hue loci are also quite similar except for unitary yellow. But the saturation contours of Sobagaki

ILL. A PREDICTIONS

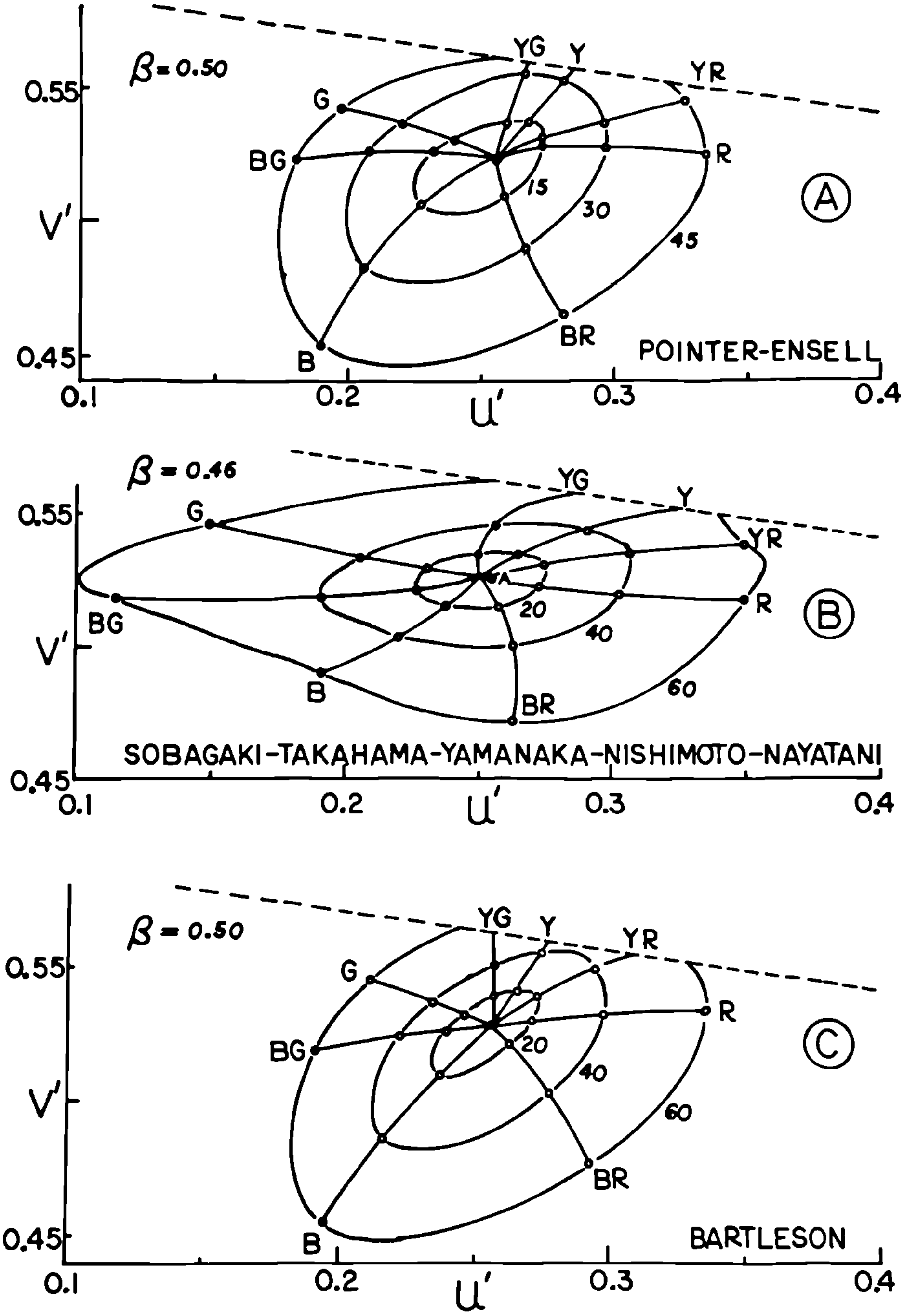
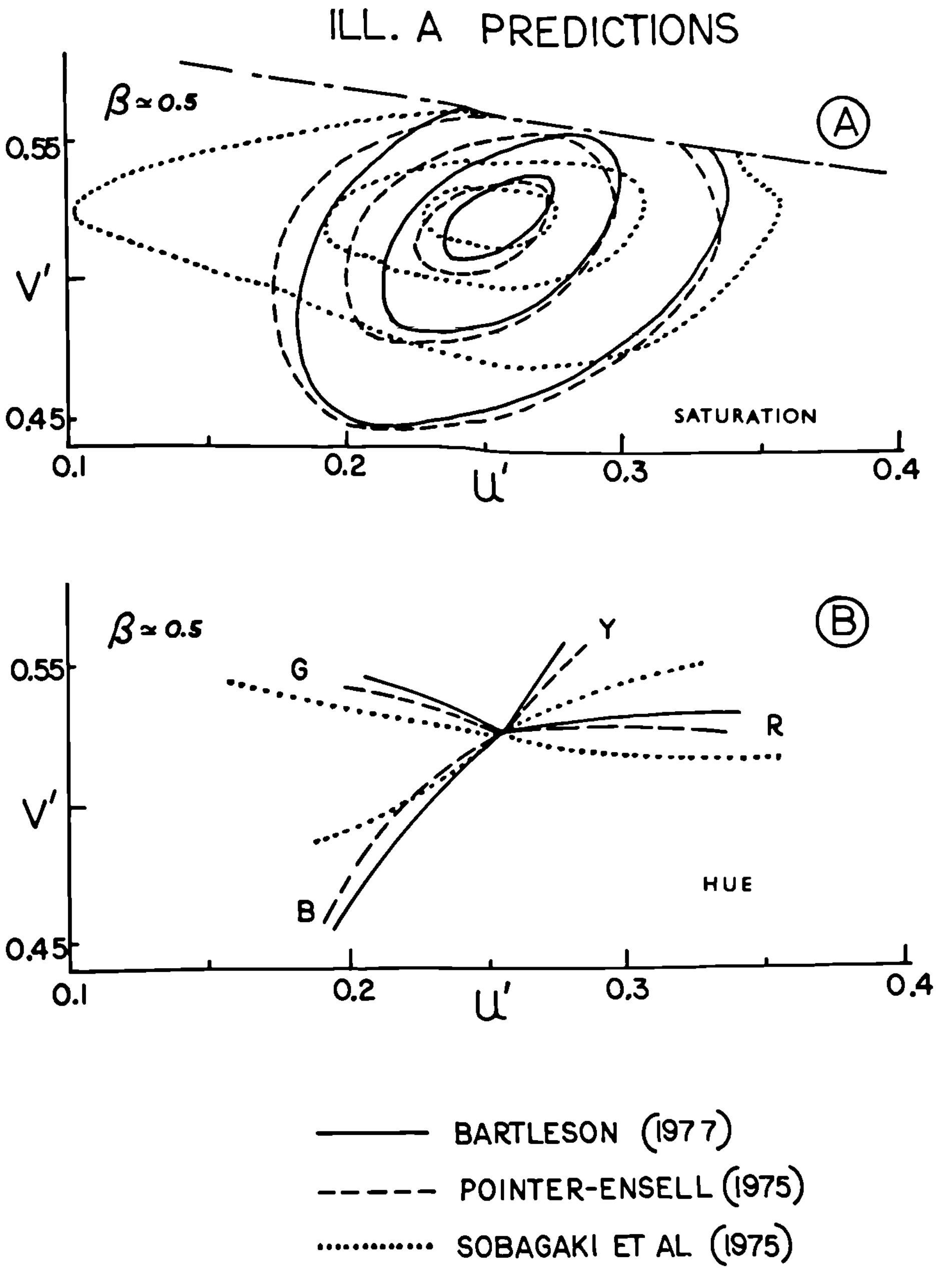


Figure 54



ILL. A PREDICTIONS
β ≃ 0.5
A
0.55
V′
0.45
SATURATION
0.1
0.2
0.3
0.4
u′
β ≃ 0.5
B
G
Y
R
B
HUE
BARTLESON (1977)
POINTER-ENSELL (1975)
SOBAGAKI ET AL (1975)

Figure 55

et al are quite different from the others.

The comparisons of Figures 54 and 55 are all among results of experiments in which the same method was used; magnitude estimation. It is also of interest to compare the results of this research with those determined by different experimental methods. To do this, the work of Helson, Judd and Warren (1952)[138] - using memory matching techniques - and that of Burnham, Evans and Newhall (1957)[61] - using haploscopic matching - were used. Those works provide means for computing corresponding chromaticities for Munsell samples viewed under CIE Illuminant A rather than C. Accordingly, a series of 30 Munsell notations were used to derive sensory physical maps analogous to those of Figure 54. They are shown in Figure 56.

Ten Munsell Hues are shown; the five Munsell primaries and their mid-point intermediates. Chromaticity for each Hue is shown at Munsell Chroma levels of 2, 6, and 10; corresponding approximately to saturations of 20, 40, and 60 of the present work. Munsell Value 5 (luminance factor of approximately 0.2) was used in the computations. The experimental results derived here were expressed in equivalent Munsell notation by overlaying the D_{65} Munsell grid on the D_{65} map of the data listed in Appendix M, then converting the Munsell notation to the scales of the present work, and finally determining the chromaticities for those scale values from the illuminant A map of Appendix M. The Helson-Judd-Warren map was constructed from their published linear transform equations. The Burnham-Evans-Newhall map was constructed from their published empirical transformation matrix.

The Burnham et al map is quite similar to the one from this work. But, again, the third map differs significantly from the other two. The general nature of the Helson et al map is reminiscent of that found by Sobagaki et al.

The Burnham et al map is not centered on the CIE Illuminant A chromaticity point. According to their results, that point would appear slightly yellowish-green.

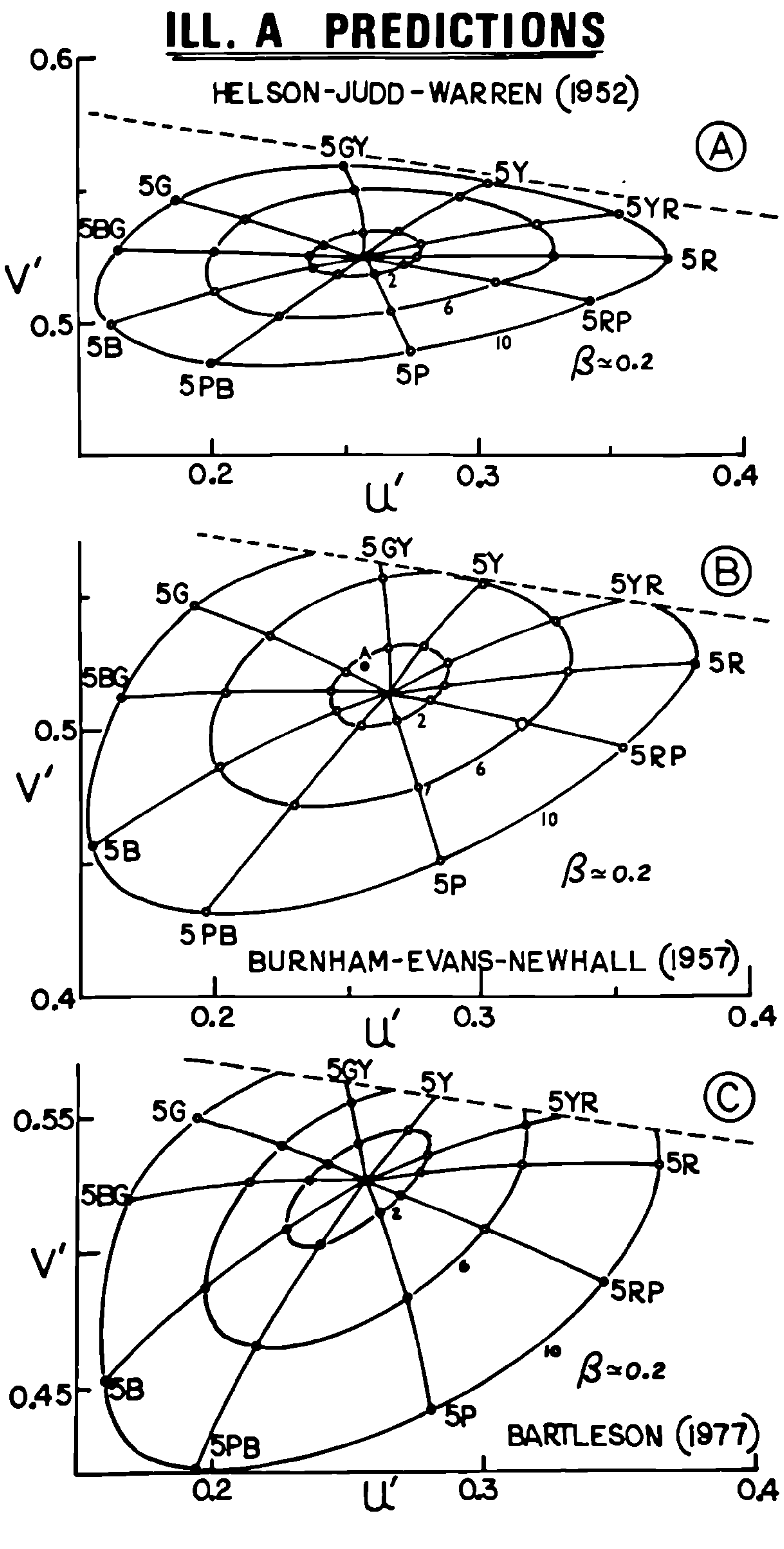

ILL. A PREDICTIONS
HELSON-JUDD-WARREN (1952)
A
5GY
5Y
5YR
5G
5BG
5R
5RP
5B
5PB
5P
2
6
10
β≃0.2
0.6
0.5
V′
0.2
0.3
0.4
u′
B
5GY
5Y
5YR
5G
5BG
5R
5RP
5B
5P
5PB
A
2
6
10
β≃0.2
BURNHAM-EVANS-NEWHALL (1957)
0.5
0.4
V′
0.2
0.3
0.4
u′
C
5GY
5Y
5YR
5G
5BG
5R
5RP
5B
5P
5PB
2
6
10
β≃0.2
BARTLESON (1977)
0.55
0.45
V′
0.2
0.3
0.4
u′

Figure 56

ILL. A PREDICTIONS

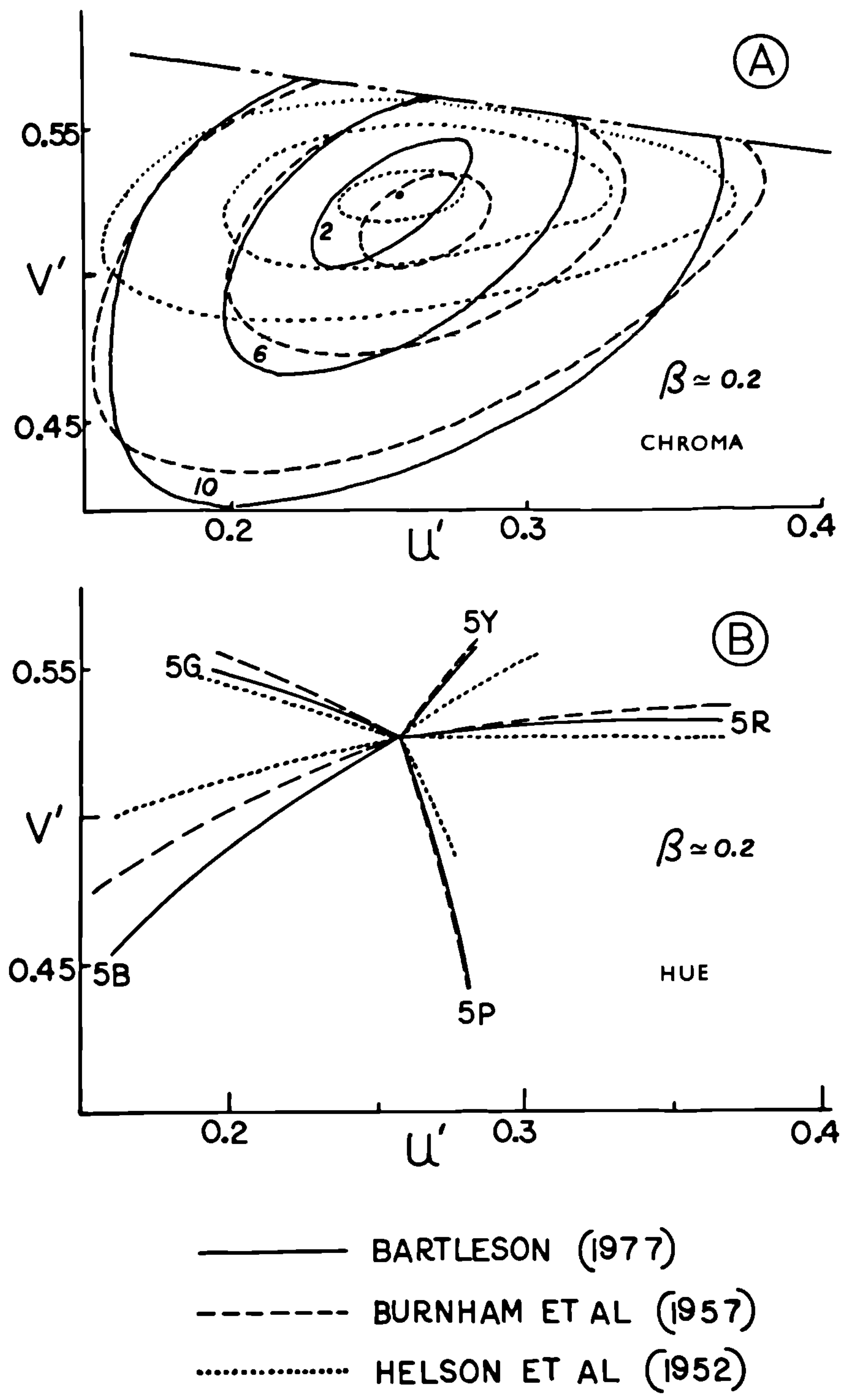


Figure 57

However, the adapting luminances in the Burnham-Evans-Newhall study were only about 85.7 $cd \cdot m^{-2}$ (25 foot-lamberts surround). That luminance is below the level of 200 $cd \cdot m^{-2}$ estimated here as a representative minimum required for adaptation to proceed to the point where the surround will appear white. Accordingly, the decentering of their contours with respect to the illuminant point may be a valid reflection of the conditions of their experiment rather than an artifact of the transformation.

Figure 57 shows superimposed hue and saturation loci from the three experiments. Again, the largest differences are in saturation contours. The Burnham et al contours are very similar to those of this work; except for the lowest saturation (or Munsell Chroma) which probably is a consequence of the discrepancy between illuminant point and predicted neutral point in the Burnham-Evans-Newhall work. The Helson-Judd-Warren saturation contours are different from the others. The hue loci of Burnham et al were translated in u',v' to force coincidence of the neutral point with the chromaticity for CIE Illuminant A. The translated hue loci are close to those of the present work, with the exception of that for Munsell 5B. Hue loci of the Helson et al work differ most from those found here in the region of Munsell 5Y and 5B.

It is well to note that the linear transform used by Helson, Judd and Warren was not considered wholly satisfactory for characterizing the results. They stated that: "It is evident that there is a general agreement between observation and theory, but in isolated cases the hue changes found are very different in amount and sometimes even in direction from those predicted" (Helson et al 1952, p.232)[138]. Inspection of their Figure 1 on page 231 of the publication, in which observed and predicted shifts are shown in Munsell polar coordinates, suggests that the raw experimental data may not differ quite as much in hue from that of the present work as is suggested by Figure 57b. Similarly, the Chroma shifts actually observed are not quite so large in the red and green directions as those shown in Figure 57. But these differences are not such as to alter substantially the general relations illustrated. The Helson-Judd-Warren results are closer in form to those of Sobagaki et al even when the observed rather than predicted data are considered.

The graphs of Figures 54 through 57 indicate that the general shapes of the contours derived here agree reasonably well with those from other experiments. There is close agreement with one other direct scaling experiment and with the haploscopic work. However, the saturation contours determined here differ in much the same manner as do those two sets of results from the memory matching experiment and one other direct scaling work. Those latter results show horizontally elongated saturation contours compared with the ones found here. Computations of predictions by MacAdam's (1963)[234] power transform, made for another purpose by M. R. Pointer (private communication, 1976), also show this horizontal elongation characteristic. It is a curious fact that there seem to be two generic types of result. They are not distinguished by experimental method. The horizontal form derives from three quite different techniques: memory matching, differential retinal conditioning, and direct scaling. The second form is found in results of two direct scaling experiments and a haploscopic study. There may be uncontrolled factors that are responsible for these differences, but that seems less likely than if they were associated with differences in experimental method. For the present, it would appear that there are unexplained differences among the results of various representative studies that tend to define two classes of results. Perhaps these discrepancies merely represent the extent of variability among results of different experiments.

The results of Helson et al and those of MacAdam cannot be evaluated directly in terms of agreement with Munsell Renotation contours under CIE Illuminants D_{65} or C. Those of Sobagaki et al, Pointer and Ensell, Burnham et al, and the present work can be used to reconstruct the Munsell map. It is probably significant that where such a direct comparison can be made, only one class of results is concordant with Munsell contours; and that is not the horizontally elongated class. The results reported here do agree very well with the Munsell Renotation array. This constitutes a form of validation. Both the massive number of observations involved and the extensive practical application of Munsell data lend support to their validity. Agreement with Munsell data seem to provide a favorable weighting for that class of results showing concordance with Munsell contours.

VI. Conclusions

The research described here has undertaken to study chromatic adaptation by applying methods of direct scaling to the color appearances of stimuli perceived under different conditions of adaptation. It differs from previous studies of chromatic adaptation, in a number of ways.

By measuring color appearance directly, the data collected permit examination of adaptationally induced color changes of invariant stimuli. Those changes have been expressed in response diagrams, on chromaticity maps, as corresponding adaptational metamers, and in a number of other psychophysical relations.

The study has involved measurement of color attributes resulting from variations in (1) correlated color temperature of adapting illuminants, (2) illuminance, (3) luminance factor, and (4) surround induction conditions. This factorial approach to the problem yields information about changes in color appearance throughout the entire color solid rather than being restricted to a single planar section of that solid.

A distinction has been made between absolute and relative attributes of perceived color. It has been shown that inferences drawn from data depend significantly on the kind of attribute that is addressed. For example, relative saturation is invariant with illuminance, but absolute saturation depends very much on illuminance. In the past, failure to make such distinctions has led to confusion in attempts to interpret the results of various experiments.

The observers here were subjected to a training program before embarking on the main experimental labors. That program was intended to familiarize the observers with the color appearance phenomena they would encounter in the main experiment and to help them learn to express their color perceptions in a consistent manner. In addition, the training phase required observers to scale color appearances by magnitude production methods as well as by magnitude estimation, thereby generating an independent set of data for use in evaluating internal consistency of results.

Evaluations of both internal and external consistency indicate that the data generated in this research have high precision for direct scaling and are suitably valid.

The results show that chromatic adaptation induces smooth, continuous changes in color appearance with variation in correlated color temperature of adapting illumination. The nature of these induced changes depends upon illuminance and luminance factors of surface color stimuli, but the <u>relative</u> changes are the same for all levels of illuminance and luminance factor studied here. The results indicate the kinds of variations in appearance that are associated with various levels of each of these parameters.

Saturation, or what has been called colorfulness, is most susceptible to change with variation in conditions of stimulation. Saturation is highly dependent upon illuminance and luminance factor in addition to color temperature of adapting illumination. The nature of these dependencies is systematic and explicit in the results presented here.

The hue appearance of a given sample depends primarily upon color temperature of adapting illumination. Little or no shift in hue was found for the range of illuminances and luminance factors investigated here. But hue shifts vary greatly according to the saturation level of stimuli. In general, the hues of all stimuli change with chromatic adaptation but there are important exceptions.

Unitary hues - red, green, and blue hues - of maximal saturation tend to have invariant wavelengths over the range of adaptation conditions studied here. This finding militates against a simple coefficient rule for describing the adaptation process.

Simple multiplicative changes in visual sensitivity are also ruled out by results for saturation. Contours of colorimetric purity versus dominant wavelength for constant-saturation appearances are related to threshold chromatic purity functions by power transforms. The exponents of those power transforms vary systematically with correlated color temperature of adapting illumination. The present data indicate, for the first time, that purity contours undergo continuous compression from low to high saturation. This finding is a consistent supplement to the fact that different compressions have been found for purity thresholds depending upon whether they represent the first saturation increment from 'white' or the first decrement from spectral lights.

These purity functions are shown to be descriptively analogous to a fundamental aspect of the perception of colorfulness. That mechanism is apparently responsible for a number of hitherto seemingly unrelated phenomena of color including the Helmholtz-Kohlrausch effect, zero gray content, chromatic strength, saturation or colorfulness, constants of saturation psychophysical functions, and the constants of lightness psychophysical equations for chromatic stimuli.

The theoretical chromatic purity function is derived from opponent chromatic response functions which, in turn, are based on fundamental sensitivity curves. In the past, greatest attention has been attached to determining fundamental sensitivities from studies of chromatic adaptation. The work presented here suggests that more attention should be given to chromatic response functions and their derivative chrominance and chromatic purity functions. The hue scaling of this work provides directly hue coefficient functions of wavelength. Psychophysical maps of saturation contours scaled here may be expressed as chromatic purity functions. It is also suggested that chrominance components may explain results of adaptation to monochromatic spectral lights. In short, there appears to be a multiplicity of information that may be used to infer chromatic response functions and underlying fundamental sensitivities in ways that have not been used in previous studies of chromatic adaptation.

The data of this research provide means for carrying out analyses of those kinds. The data should subsequently be analyzed in detail with the objective of determining implied chromatic opponent response functions. Particularly, the manner in which those functions vary with chromatic adaptation should be studied. A mathematical expression of the transformation of adaptational metamers should be based on the nature of those changes.

For the present, however, the data set forth here offer a reasonably complete description of changes in color appearances of stimuli as chromatic adaptation varies over ranges that are representative of those typically encountered in industrial and commercial situations. Since the data describe changes throughout the entire solid of surface color perceptions, they afford an opportunity to evaluate proposed transformation methods with a thoroughness that has not been possible before, as well as offering the basis for developing new, multi-dimensional transformation expressions.

- - -

Appendix A

Spectral power distributions of surround illumination:

Wavelength (nm)	"D_{65}"	"D_{44}"	"A"
400	30.2		11.6
410	48.0		16.2
420	67.6		20.7
430	91.2		25.4
440	118.6		31.1
450	135.6		34.2
460	148.6		36.4
470	157.7		38.2
480	164.6		40.9
490	165.2		43.1
500	159.4		45.9
510	158.1		53.1
520	148.2		62.4
530	136.3		72.8
540	125.1		83.6
550	112.5		93.1
560	100.0		100.0
570	91.8		105.3
580	89.4		111.4
590	88.8		115.3
600	88.8		118.5
610	94.2		122.8
620	106.1		129.9
630	125.1		137.2
640	157.7		148.4
650	204.3		160.3
660	234.6		169.2
670	271.3		163.2
680	251.9		148.4
690	215.6		126.8
700	174.7		100.3
$cd.m^{-2}$:	1,080	1,030	1,090
x :	.3140	.3454	.4467
y :	.3276	.3584	.4072
u' :	.1978	.2090	.2560
v' :	.4683	.4880	.5243
K :	6,510	4,400	2,840

Appendix B

Chromaticity coordinates of magnitude estimation stimuli:

Stimulus	x	y	u'	v'
1	.3757	.4298	.2029	.5223
2	.4067	.4148	.2271	.5211
3	.4500	.4142	.2546	.5273
4	.5176	.3147	.3606	.4934
5	.3672	.3494	.2274	.4869
6	.2208	.4325	.1140	.5024
7	.4365	.4749	.2231	.5462
8	.3654	.5490	.1650	.5579
9	.4999	.3945	.2969	.5273
10	.2775	.5959	.1157	.5589
11	.3979	.4848	.1984	.5439
12	.4502	.3458	.2882	.4980
13	.2872	.2838	.1970	.4380
14	.6380	.3597	.4225	.5360
15	.3513	.4277	.1891	.5181
16	.5256	.4651	.2792	.5559
17	.4400	.3761	.2653	.5103
18	.6361	.2851	.4942	.4983
19	.3803	.3904	.2197	.5075
20	.4781	.4563	.2543	.5461
21	.1497	.3855	.0817	.4735
22	.1628	.1753	.1363	.3301
23	.2526	.1122	.2630	.3261
24	.3610	.1828	.3229	.3680

Appendix C

Transmittances of magnitude estimation filters:

Wavelength (nm)	1	2	3	4	5	6	7
400	.077	.082	.041	.200	.184	.082	.031
410	.089	.095	.045	.208	.202	.101	.031
420	.096	.101	.049	.210	.215	.124	.031
430	.103	.107	.052	.200	.222	.148	.033
440	.109	.112	.055	.182	.225	.173	.035
450	.112	.118	.057	.160	.223	.200	.040
460	.116	.123	.061	.135	.215	.229	.050
470	.121	.125	.066	.111	.200	.258	.066
480	.125	.125	.071	.086	.184	.279	.085
490	.125	.124	.076	.064	.165	.293	.111
500	.126	.121	.077	.050	.146	.298	.142
510	.130	.120	.074	.040	.130	.293	.160
520	.129	.121	.072	.031	.114	.278	.165
530	.127	.119	.071	.027	.103	.251	.166
540	.125	.119	.070	.033	.097	.211	.163
550	.124	.120	.071	.042	.092	.160	.159
560	.120	.119	.073	.045	.091	.106	.154
570	.115	.119	.076	.053	.095	.069	.150
580	.109	.122	.085	.088	.103	.050	.146
590	.104	.124	.095	.157	.115	.036	.142
600	.098	.125	.103	.229	.123	.022	.139
610	.092	.124	.108	.275	.126	.016	.141
620	.084	.121	.109	.297	.120	.016	.147
630	.076	.116	.107	.305	.110	.020	.151
640	.072	.115	.107	.309	.102	.025	.152
650	.070	.114	.108	.314	.099	.031	.152
660	.068	.116	.109	.317	.097	.040	.152
670	.067	.116	.110	.320	.096	.050	.160
680	.065	.116	.111	.320	.093	.058	.172
690	.065	.116	.112	.322	.091	.064	.184
700	.070	.121	.116	.329	.093	.076	.192

(continued)

Appendix C

(continued):

Wavelength (nm)	8	9	10	11	12	13	14
400	.002	.060	.004	.031	.117	.464	.001
410	.002	.058	.005	.032	.125	.510	.001
420	.002	.056	.008	.033	.130	.561	.001
430	.002	.056	.011	.035	.133	.607	.001
440	.003	.059	.017	.037	.137	.617	.001
450	.010	.061	.027	.042	.139	.605	.001
460	.024	.067	.046	.050	.136	.578	.001
470	.049	.074	.071	.060	.127	.538	.001
480	.079	.082	.095	.072	.115	.490	.001
490	.109	.091	.122	.088	.100	.432	.001
500	.134	.099	.151	.110	.088	.372	.001
510	.151	.096	.180	.124	.078	.315	.002
520	.160	.087	.206	.128	.069	.255	.002
530	.165	.079	.226	.127	.062	.201	.006
540	.167	.074	.231	.124	.060	.164	.012
550	.163	.073	.219	.121	.058	.137	.020
560	.152	.075	.187	.114	.061	.108	.030
570	.138	.085	.138	.106	.068	.083	.050
580	.118	.106	.084	.100	.082	.077	.089
590	.091	.137	.034	.096	.106	.084	.155
600	.062	.171	.008	.091	.133	.092	.236
610	.043	.198	.002	.082	.156	.093	.296
620	.037	.215	.001	.073	.172	.101	.326
630	.035	.224	.001	.064	.180	.144	.337
640	.035	.229	.002	.058	.186	.242	.343
650	.039	.232	.002	.057	.189	.384	.347
660	.049	.235	.002	.056	.193	.536	.352
670	.063	.236	.008	.056	.193	.632	.354
680	.076	.238	.017	.053	.192	.685	.358
690	.090	.242	.029	.053	.194	.711	.362
700	.103	.254	.041	.058	.199	.721	.371

(continued)

Appendix C

(continued):

Wavelength (nm)	15	16	17	18	19	20	21
400	.075	.001	.080	.327	.573	.153	.045
410	.087	.001	.087	.308	.605	.125	.067
420	.098	.001	.095	.266	.635	.112	.096
430	.105	.001	.098	.202	.662	.114	.139
440	.109	.001	.103	.133	.688	.130	.195
450	.112	.001	.107	.073	.716	.161	.277
460	.115	.001	.104	.032	.742	.211	.379
470	.120	.001	.102	.012	.758	.271	.484
480	.123	.002	.098	.002	.761	.340	.555
490	.127	.008	.092	.001	.755	.416	.593
500	.127	.016	.086	.001	.736	.498	.590
510	.126	.029	.080	.001	.698	.580	.543
520	.122	.047	.075	.001	.657	.655	.451
530	.119	.070	.071	.001	.631	.720	.323
540	.116	.093	.068	.001	.592	.774	.191
550	.112	.113	.068	.001	.517	.811	.088
560	.105	.127	.070	.001	.465	.836	.035
570	.098	.136	.074	.001	.501	.852	.020
580	.092	.144	.085	.003	.570	.864	.017
590	.086	.150	.100	.048	.575	.870	.016
600	.079	.152	.117	.212	.524	.873	.015
610	.070	.151	.129	.422	.483	.875	.014
620	.060	.149	.133	.568	.476	.878	.014
630	.050	.148	.135	.641	.486	.878	.015
640	.046	.146	.136	.679	.494	.878	.016
650	.044	.146	.138	.699	.509	.878	.017
660	.043	.148	.140	.711	.550	.880	.018
670	.042	.149	.141	.721	.599	.880	.020
680	.040	.149	.140	.727	.642	.880	.021
690	.040	.150	.140	.733	.678	.882	.023
700	.044	.155	.145	.737	.700	.884	.027

(continued)

(continued):

Wavlength (nm)	22	23	24
400	.185	.136	.371
410	.255	.187	.409
420	.341	.257	.439
430	.444	.321	.443
440	.508	.309	.403
450	.535	.248	.343
460	.528	.171	.266
470	.497	.106	.195
480	.442	.062	.137
490	.368	.034	.088
500	.291	.022	.056
510	.212	.018	.039
520	.133	.015	.029
530	.074	.015	.022
540	.042	.016	.019
550	.023	.016	.019
560	.012	.016	.019
570	.009	.016	.019
580	.009	.016	.019
590	.009	.016	.020
600	.010	.016	.028
610	.009	.016	.055
620	.009	.017	.093
630	.011	.018	.150
640	.020	.026	.246
650	.053	.071	.375
660	.115	.210	.511
670	.158	.380	.601
680	.163	.514	.657
690	.160	.613	.692
700	.174	.665	.712

Appendix D

Spectral power distribution of unfiltered stimulus beam:

Wavelength (nm)	Relative power
400	18.2
410	21.4
420	24.3
430	28.4
440	31.7
450	37.5
460	43.9
470	47.6
480	54.0
490	58.7
500	66.4
510	71.3
520	76.3
530	80.9
540	87.7
550	95.1
560	100.0
570	104.0
580	103.8
590	107.8
600	106.7
610	106.8
620	104.3
630	99.3
640	96.8
650	86.8
660	84.1
670	74.7
680	61.5
690	55.1
700	51.3

Appendix E

Spectral error factors of UBD colorimeter:

Wavelength (nm)	$e_{\bar{x}}$	$e_{\bar{y}}$	$e_{\bar{z}}$
380	-.0014	0	-.0065
390	-.0042	-.0001	-.0201
400	-.0143	-.0004	-.0679
410	-.0407	-.0004	-.1929
420	-.0405	-.0006	-.1535
430	-.0179	-.0031	+.0085
440	-.0178	-.0092	-.0143
450	+.0018	-.0138	0
460	+.0211	-.0188	-.0341
470	+.0554	-.0148	+.0271
480	+.0806	+.0034	+.1110
490	+.0743	+,0399	+.0923
500	+.0482	+.0811	+.0062
510	+.0127	+.0915	-.0503
520	-.0455	+.0319	-.0454
530	-.0656	-.0195	-.0378
540	-.0427	-.0247	-.0194
550	+.0032	-.0096	-.0087
560	-.0134	+.0050	-.0039
570	-.0619	-.0084	-.0021
580	-.0885	+.0018	-.0017
590	-.0508	+.0149	-.0011
600	0	+.0073	-.0008
610	+.0160	-.0065	-.0003
620	-.0138	-.0112	-.0002
630	-.0246	-.0183	0
640	-.0268	-.0146	0
650	-.0144	-.0076	0
660	+.0014	-.0011	0
670	+.0075	+.0018	0
680	+.0067	+.0006	0
690	+.0070	+.0010	0
700	+.0047	+.0007	0
710	+.0025	+.0007	0
720	+.0015	-.0003	0
730	+.0001	-.0005	0
740	-.0007	-.0003	0
750	-.0003	-.0001	0
$\bar{e}$:	.0245	.0123	.0240
S_e:	2.41%	2.01%	2.50%

Appendix F

Standard deviations:

Hue:

Stimulus	A	B	C	D	E	F	G	Avg.
				Observers				
1	3.0	4.4	1.1	1.1	3.0	0.0	1.1	9.8
2	1.5	3.0	0.0	1.1	4.4	3.0	2.2	5.8
3	1.5	4.4	1.1	2.2	1.5	3.0	2.2	4.5
4	1.5	5.9	3.3	8.9	3.0	1.5	1.7	5.7
5	0.7	3.0	0.0	1.1	3.0	0.0	3.3	5.6
6	0.7	0.0	2.2	0.0	0.0	0.0	0.0	0.8
7	0.0	4.4	2.2	2.2	7.4	1.5	2.2	2.8
8	0.7	3.0	7.8	0.0	0.0	0.7	4.4	5.1
9	0.0	3.0	1.1	0.0	3.0	1.5	0.0	5.3
10	1.5	4.4	1.1	6.6	3.0	0.7	2.2	6.5
11	0.0	3.0	0.0	3.3	5.9	1.5	0.0	1.6
12	2.2	3.0	1.1	4.4	10.3	3.0	2.2	6.6
13	1.5	0.0	1.1	2.2	3.0	0.0	2.2	4.5
14	0.7	0.0	0.0	4.4	4.4	0.7	2.2	7.3
15	1.5	0.0	5.5	4.4	8.9	1.5	1.1	8.4
16	0.7	3.0	1.1	1.1	4.4	3.0	0.0	5.4
17	1.5	3.0	1.1	2.2	8.9	0.0	0.0	3.5
18	2.2	3.0	1.1	0.0	1.5	1.5	0.0	7.2
19	1.5	1.5	6.5	0.0	8.9	0.0	4.4	14.2
20	0.0	4.4	10.0	0.0	4.4	1.9	4.4	9.3
21	1.5	5.9	0.0	0.0	3.0	0.7	0.0	2.7
22	3.0	4.4	0.0	1.1	1.5	0.0	1.1	3.1
23	1.5	3.0	0.0	13.3	4.4	3.0	2.2	4.2
24	1.5	5.9	0.0	1.1	0.0	1.5	2.2	2.1
MPE:	1.5	2.1	2.4	1.6	2.6	0.9	1.4	3.7

Saturation:

1	7.7	53.1	9.3	46.7	10.3	0.0	25.4	22.0
2	2.6	10.4	29.5	0.0	44.3	20.6	44.3	17.3
3	7.1	27.2	17.7	13.7	33.2	0.0	29.5	5.8
4	5.5	0.0	13.6	13.7	41.6	18.9	13.7	7.6
5	29.9	113.1	25.3	19.8	39.3	0.0	95.4	46.6
6	5.0	17.1	7.1	5.7	42.3	18.5	0.0	17.3
7	9.8	23.1	26.9	0.0	44.2	6.4	0.0	15.2
8	7.6	46.7	0.0	59.1	118.0	35.6	35.6	32.1
9	5.1	5.7	0.0	0.0	8.0	7.9	11.9	5.8
10	19.9	16.9	18.3	23.1	48.2	17.8	0.0	14.0
11	2.3	10.6	6.1	5.7	69.0	5.9	0.0	10.6
12	17.2	35.4	25.3	9.3	39.3	68.2	59.1	22.9
13	7.5	5.7	7.1	0.0	8.8	7.7	0.0	7.6
14	5.3	0.0	0.0	0.0	26.5	10.7	13.7	15.9
15	5.2	0.0	7.7	16.2	17.7	30.8	13.5	25.5
16	10.6	59.0	88.7	25.4	17.7	44.8	0.0	31.7
17	6.6	10.4	23.1	25.3	12.6	0.0	19.8	14.5
18	4.0	52.2	17.7	7.0	19.7	24.4	0.0	16.9
19	5.2	0.0	58.7	25.1	37.9	25.7	25.1	24.4
20	10.0	101.3	25.1	0.0	63.4	31.4	0.0	29.4
21	2.4	0.0	21.3	7.0	30.8	23.4	13.7	14.0
22	7.8	50.7	5.7	11.7	0.0	9.0	0.0	21.5
23	3.1	71.0	25.4	25.4	39.3	56.7	0.0	24.7
24	7.5	11.1	3.0	0.0	37.3	9.7	29.5	11.1
MPE:	8.1	36.1	18.5	16.0	37.6	19.6	20.3	18.9

Appendix G

Individual and mean estimates of hue and saturation:

D_{65} Hue;

Stm.	A	B	C	D	E	F	G	$\bar{X}$
1	34.2	31.6	47.2	40.0	45.8	32.7	37.5	38.4
2	30.0	22.5	39.3	20.0	42.5	21.7	17.5	27.6
3	41.9	42.5	46.8	46.3	43.3	43.7	48.3	44.7
4	47.5	49.4	52.8	52.5	50.8	47.8	52.5	50.5
5	7.5	10.8	-5.6	6.8	-5.0	8.3	8.3	4.4
6	70.0	72.3	71.8	74.2	78.3	72.3	72.6	73.1
7	21.0	19.3	24.9	22.5	26.7	21.7	16.7	21.8
8	31.0	28.6	34.2	32.5	42.5	25.0	27.5	31.6
9	50.0	50.0	57.5	52.5	49.2	47.8	56.7	52.0
10	40.0	35.8	47.2	44.7	40.8	41.3	41.7	41.6
11	88.3	88.3	90.0	83.7	88.3	90.0	80.7	87.0
12	-5.8	6.6	-3.2	5.0	8.3	2.5	7.5	3.0
13	45.0	47.5	49.4	46.7	41.7	46.3	50.0	46.7
14	92.8	100.0	97.5	97.5	94.2	98.8	98.8	97.1
15	17.5	15.0	18.8	16.7	29.2	17.8	15.0	18.6
16	-4.2	7.5	-3.2	5.7	5.0	5.3	10.8	3.8
17	40.8	40.8	48.4	45.3	45.8	42.5	49.3	44.7
18	-5.6	0.0	-1.3	1.6	5.0	0.0	0.7	0.1
19	12.5	13.2	0.6	5.6	8.2	15.8	17.5	10.5
20	17.2	20.0	33.2	32.5	41.7	23.8	28.3	28.1
21	6.6	0.8	0.2	4.3	11.7	1.3	1.3	3.7
22	83.2	92.5	82.5	100.0	82.5	112.5	N	92.2
23	10.6	12.5	4.2	6.7	14.2	9.2	12.5	10.0
24	91.2	92.5	90.0	83.3	92.5	91.2	90.7	90.2
Snd	N	95.8	N	116.7	N	80.4	75.0	92.0

D_{65} Saturation;

Stm.	A	B	C	D	E	F	G	$\bar{X}$
1	42.1	50.8	44.3	43.5	40.0	42.4	41.6	43.7
2	45.8	60.5	44.3	47.0	36.1	49.5	43.8	46.8
3	46.6	64.6	55.3	77.8	54.6	51.5	59.2	57.5
4	67.6	67.5	85.2	50.8	54.6	60.2	72.5	64.6
5	35.5	12.2	25.0	29.5	36.1	20.3	25.8	24.5
6	63.2	67.5	91.0	61.7	63.6	79.1	72.5	74.1
7	51.6	46.5	65.2	61.7	58.9	66.3	55.0	58.9
8	38.7	21.6	49.5	34.5	31.7	31.1	31.6	31.6
9	66.5	87.8	98.0	102.1	86.6	87.1	86.4	89.1
10	27.5	50.8	41.1	34.5	58.9	44.1	55.0	42.7
11	61.1	60.5	71.6	77.8	117.8	114.4	76.2	81.3
12	49.9	51.9	47.7	40.2	44.4	34.9	46.0	45.7
13	84.3	67.5	69.0	72.1	86.6	71.7	72.5	77.6
14	118.4	75.3	79.9	124.0	101.0	101.8	86.4	100.0
15	49.9	60.5	45.1	55.0	49.2	55.7	59.2	53.7
16	44.3	43.6	33.6	26.3	31.7	32.9	37.7	36.3
17	30.0	51.9	41.1	40.2	31.7	47.6	51.0	40.7
18	77.4	67.5	61.7	55.0	49.2	71.7	63.9	66.1
19	46.6	43.6	28.9	29.5	36.1	31.1	31.6	35.5
20	41.4	45.5	35.5	40.2	31.7	37.0	31.6	38.0
21	94.9	73.7	70.2	77.8	68.7	88.9	80.1	81.3
22	13.3	7.5	11.7	4.6	18.6	6.3	0.0	10.0
23	56.1	63.2	49.5	40.2	72.3	47.6	63.9	56.2
24	82.9	87.8	89.3	94.6	78.2	92.3	86.4	89.1
Snd	0.0	3.9	0.0	10.9	0.0	4.1	1.8	2.0

D_{44} Hue;

Stm.	A	B	C	D	E	F	G	$\bar{X}$
1	37.5	37.5	45.0	46.8	42.5	45.4	55.0	44.2
2	32.5	30.0	40.0	35.0	42.5	27.0	19.4	32.3
3	45.0	42.5	47.5	30.0	47.5	41.5	51.7	43.7
4	52.5	50.0	53.2	52.5	50.0	48.4	57.5	52.0
5	2.5	8.7	0.0	5.0	-5.7	18.7	6.7	5.1
6	72.5	75.0	75.0	75.0	75.0	74.0	75.0	74.5
7	21.3	22.5	25.8	29.2	30.7	25.0	20.0	24.9
8	26.3	33.7	45.0	42.5	45.0	36.8	42.5	38.8
9	53.7	52.5	57.5	55.0	55.6	52.0	61.3	55.4
10	32.5	37.5	46.3	43.7	43.4	43.4	43.2	41.4
11	85.0	87.5	82.5	82.5	85.7	82.0	84.3	84.2
12	6.3	8.7	-5.0	5.0	5.0	-0.7	8.2	8.2
13	46.3	51.3	49.0	47.5	46.8	47.5	47.5	48.0
14	98.7	100.0	97.5	97.5	101.7	96.3	99.3	98.7
15	12.5	21.3	21.2	21.3	34.2	26.2	19.0	22.2
16	2.5	12.5	1.3	3.7	10.0	7.0	15.7	7.5
17	37.5	53.7	48.8	52.5	48.4	48.0	54.5	49.1
18	97.5	100.0	97.2	102.5	105.0	100.0	97.5	100.0
19	15.0	21.3	11.3	43.7	38.3	20.7	19.0	24.2
20	27.5	37.5	32.5	42.5	40.0	35.8	35.7	35.9
21	2.5	2.5	1.6	3.7	6.7	2.5	2.5	3.1
22	77.5	77.5	77.5	75.0	76.3	75.0	75.0	76.3
23	15.0	12.5	9.4	12.5	15.0	13.3	14.3	13.1
24	87.5	87.5	90.0	88.7	97.5	90.7	89.3	90.2
Snd	N	N	N	22.5	N	94.0	100.0	72.2

D_{44} Saturation;

1	44.8	60.5	37.6	60.0	39.7	40.9	42.4	46.6
2	44.8	60.5	43.2	64.4	39.7	51.4	29.5	47.6
3	57.6	72.1	62.0	69.1	50.9	54.5	58.1	60.6
4	68.2	62.9	78.8	60.0	54.4	68.5	63.6	65.2
5	15.9	18.3	13.5	14.5	14.7	8.9	10.0	13.7
6	57.6	79.5	36.8	79.7	85.5	71.2	72.8	69.0
7	57.6	54.8	49.7	60.0	47.6	61.1	48.5	54.2
8	32.9	41.7	35.4	60.0	43.5	42.5	29.5	40.8
9	79.3	94.8	83.7	95.1	81.7	86.2	72.8	84.8
10	30.9	60.5	48.7	79.7	54.4	47.6	51.9	53.4
11	57.6	75.0	57.2	79.7	100.1	108.4	72.8	78.7
12	37.8	23.2	36.8	50.2	33.1	29.0	32.3	34.6
13	74.1	87.7	82.0	85.5	76.4	79.8	68.1	79.1
14	93.8	98.6	87.1	105.8	85.5	93.0	72.8	90.9
15	52.1	46.0	45.0	46.8	54.4	57.7	38.7	48.7
16	37.8	23.2	31.4	20.7	18.4	21.3	18.0	24.4
17	30.9	33.0	34.0	46.8	33.1	49.5	45.4	39.0
18	44.8	23.2	30.7	27.5	29.6	51.4	48.5	36.5
19	30.9	41.7	34.0	23.9	36.3	24.9	24.7	30.9
20	22.9	37.1	27.3	30.6	36.3	39.4	24.7	31.2
21	79.3	75.0	78.8	88.6	58.3	73.9	72.8	75.2
22	8.3	12.9	16.5	17.3	7.6	9.9	4.1	10.9
23	44.8	28.2	48.7	79.7	33.1	44.1	37.0	45.1
24	62.7	50.7	74.2	79.7	58.3	91.2	68.1	69.3
Snd	0.0	0.0	0.0	5.0	0.0	4.5	3.1	1.8

(continued): Appendix G

A Hue;

Stm	A	B	C	D	E	F	G	$\bar{X}$
1	42.9	43.3	59.4	69.4	45.0	50.0	53.4	51.9
2	31.7	35.8	47.5	43.1	40.0	42.5	46.3	41.0
3	44.6	45.0	48.1	53.8	41.7	47.6	48.8	47.1
4	65.2	68.3	56.9	62.5	60.0	52.8	58.1	60.5
5	80.8	85.0	77.5	85.6	87.5	N	92.5	84.8
6	72.9	75.0	75.0	75.0	75.0	75.0	75.0	74.7
7	40.0	34.2	41.3	41.3	41.7	39.2	38.8	39.5
8	50.8	47.5	55.6	61.3	47.5	49.8	57.5	52.9
9	60.0	58.3	69.4	70.0	55.8	61.7	60.0	62.2
10	42.5	45.0	49.4	50.0	32.5	45.6	46.3	44.5
11	82.5	85.0	82.5	81.9	85.0	80.6	85.0	83.2
12	83.8	88.3	84.4	92.5	101.7	93.4	95.0	91.3
13	45.8	50.0	50.6	53.8	41.7	49.3	51.5	49.0
14	87.9	100.0	96.3	95.0	107.5	97.0	96.3	97.1
15	21.7	30.0	41.9	42.5	37.5	26.4	44.4	34.9
16	85.4	89.2	95.6	85.6	90.8	95.0	100.0	91.7
17	59.2	53.3	59.4	56.3	53.3	50.0	57.5	55.6
18	86.3	90.0	88.1	90.0	105.8	96.4	97.5	93.4
19	13.3	11.7	31.3	50.0	47.5	25.0	37.5	30.9
20	45.0	35.0	56.9	60.0	44.2	48.5	55.0	49.2
21	3.8	9.2	3.8	5.0	5.0	2.0	5.0	4.8
22	81.3	83.3	75.0	75.6	76.7	75.0	76.9	77.7
23	4.2	10.8	0.0	2.5	7.5	7.5	11.3	6.3
24	87.9	87.5	85.0	90.6	90.0	87.5	88.8	88.2
Snd	19.6	21.7	21.3	15.0	N	16.7	16.9	18.5

A Saturation;

Stm	A	B	C	D	E	F	G	$\bar{X}$
1	29.9	30.3	37.8	46.8	27.6	49.6	43.3	36.8
2	41.8	48.9	45.4	64.7	49.5	53.5	49.8	49.6
3	73.0	72.4	68.1	71.3	68.8	79.6	75.3	73.9
4	83.5	82.0	83.4	69.0	72.4	85.8	80.7	81.8
5	13.1	10.3	20.6	9.8	8.8	0.0	8.1	10.3
6	91.3	58.9	81.8	92.4	93.2	87.5	99.3	86.2
7	47.8	43.1	58.7	64.7	49.5	56.6	49.8	52.5
8	25.6	29.1	51.6	42.4	23.1	34.0	31.4	32.7
9	91.3	83.7	98.4	89.5	98.1	84.2	94.8	93.3
10	41.6	60.1	52.6	60.6	44.7	60.0	62.6	55.9
11	99.8	91.0	91.4	92.4	78.1	105.6	99.3	96.4
12	34.9	44.0	40.6	46.8	36.5	25.2	28.0	35.0
13	91.3	83.7	81.8	81.2	86.4	84.2	99.3	88.5
14	122.0	96.8	94.8	89.5	86.4	90.8	80.7	96.4
15	46.7	27.9	43.8	56.8	40.4	47.8	40.4	42.0
16	20.0	19.2	26.1	29.7	40.4	25.6	22.7	24.6
17	39.9	48.9	43.8	53.2	59.1	60.0	55.8	50.9
18	69.8	48.9	68.1	69.0	78.1	57.7	62.6	64.0
19	17.9	14.1	17.1	11.2	18.0	16.0	21.7	16.0
20	29.2	22.2	16.8	24.4	26.3	37.4	37.7	26.2
21	91.3	82.0	81.8	69.0	100.6	72.4	80.7	83.7
22	57.1	60.1	55.6	32.7	49.5	42.7	62.6	51.6
23	39.9	44.0	29.2	29.7	36.5	23.3	24.9	31.2
24	95.5	87.3	91.4	71.3	82.1	97.9	73.9	88.5
Snd	1.8	2.1	2.1	1.9	0.0	2.4	2.2	1.7

Appendix H

D_{65} Hue and Saturation estimates at 3 luminance factors:

Stm	Hue 0.43	Hue 0.20	Hue 0.07	Saturation 0.43	Saturation 0.20	Saturation 0.07
1	35.3	40.8	42.6	37.3	28.0	19.3
2	25.8	27.8	26.2	52.1	32.9	20.7
3	45.9	44.6	43.4	48.8	42.2	26.6
4	52.3	53.0	55.3	49.1	51.7	30.6
5	8.9	0.7	-2.4	24.1	21.9	12.2
6	74.1	75.0	73.6	63.2	50.4	27.7
7	22.8	22.8	22.9	65.1	51.8	37.2
8	30.8	36.5	34.2	22.6	22.5	10.2
9	53.9	55.4	57.4	90.5	69.3	53.1
10	39.4	40.1	42.9	37.8	31.5	20.9
11	85.3	85.6	84.6	74.9	62.5	26.5
12	6.1	7.0	2.3	36.1	34.8	19.1
13	43.5	43.0	45.8	72.1	62.9	38.9
14	98.9	96.9	99.3	102.4	82.4	61.9
15	18.6	22.5	26.8	47.4	37.9	26.1
16	10.6	4.8	3.0	27.1	23.2	10.6
17	44.4	44.8	43.8	27.9	22.4	13.2
18	3.1	2.1	-0.6	54.2	38.9	26.4
19	18.1	12.9	9.2	24.1	19.8	9.4
20	25.4	33.1	31.4	20.7	17.1	12.4
21	5.0	5.8	2.5	91.4	58.5	41.9
22	88.2	86.3	N	2.9	2.6	0.0
23	14.8	13.6	12.5	50.5	41.3	24.9
24	89.9	89.2	87.1	75.6	57.2	30.4

Mean for 3 observers

Appendix I

A Hue and Saturation estimates at 3 luminance factors:

Stm	Hue 0.43	Hue 0.20	Hue 0.07	Saturation 0.43	Saturation 0.20	Saturation 0.07
1	40.0	40.0	41.3	20	15	12
2	32.5	35.0	33.7	20	20	13
3	42.5	40.0	43.7	40	30	22
4	60.0	60.0	58.7	50	50	22
5	82.5	82.5	80.0	20	12	10
6	73.7	72.5	72.5	70	60	35
7	30.0	31.2	35.0	25	20	15
8	45.0	32.5	35.0	20	15	12
9	65.0	63.7	65.0	150	110	75
10	41.2	41.2	42.5	30	20	10
11	82.5	82.5	83.7	90	50	39
12	92.5	92.5	91.7	30	20	17
13	42.5	43.7	45.0	120	80	53
14	97.5	97.5	96.7	160	120	85
15	22.5	22.5	23.7	35	25	16
16	97.5	96.7	95.0	30	20	15
17	57.5	57.5	55.0	50	20	10
18	90.0	87.5	90.0	75	50	38
19	22.5	23.7	25.0	20	15	10
20	37.5	40.0	40.0	12	10	7
21	10.0	7.5	6.7	85	70	56
22	82.5	80.0	78.7	60	55	33
23	11.3	10.0	10.0	45	40	30
24	87.5	86.7	85.0	130	100	70

Mean for 1 observer

Appendix J

Hue and saturation estimates at 500 $cd \cdot m^{-2}$:

D_{65} Hue;

Stm	A	B	C	D	E	F	G	$\bar{X}$
1	35.0	32.7	45.0	44.3	42.5	35.0	40.0	39.2
2	30.0	25.0	46.5	36.0	31.0	24.7	17.5	30.1
3	44.3	40.5	48.0	45.0	46.0	43.0	47.5	44.9
4	45.0	49.4	49.5	53.0	49.0	48.7	52.5	49.6
5	7.5	2.5	10.0	7.0	2.0	13.0	10.0	7.4
6	72.3	75.0	73.3	75.0	77.5	73.7	73.7	74.4
7	22.5	20.3	23.3	20.0	24.7	22.5	18.7	21.7
8	29.3	25.4	40.0	47.0	41.5	28.3	33.7	35.0
9	48.3	50.0	51.3	52.5	54.0	51.3	55.0	51.8
10	44.7	37.5	45.0	45.0	45.5	35.0	43.3	42.3
11	88.3	87.5	82.5	81.0	88.3	80.3	83.7	84.5
12	0.7	6.6	3.7	6.3	6.5	5.0	6.3	5.0
13	45.0	45.0	48.3	45.5	43.0	43.3	50.0	45.7
14	94.3	99.5	92.5	99.5	102.5	98.5	99.4	98.0
15	17.3	16.7	20.0	17.0	16.5	21.5	15.0	17.7
16	2.3	5.0	12.5	5.0	6.3	14.2	15.0	8.6
17	40.7	41.5	47.5	45.0	50.0	45.7	51.7	46.0
18	0.0	0.3	2.5	5.0	7.5	0.0	0.6	2.3
19	12.5	12.5	21.7	12.0	28.8	19.3	17.5	17.8
20	20.0	25.7	42.5	41.5	43.7	26.8	37.5	34.0
21	5.0	1.5	3.7	5.0	11.3	1.5	1.7	4.2
22	92.5	97.3	N	N	N	107.5	N	99.1
23	7.5	10.3	12.5	7.5	13.8	13.3	12.5	11.1
24	91.7	92.5	90.0	90.0	91.3	90.7	88.3	90.6
Snd	N	N	N	20.0	75.0	12.5	N	35.8

D_{65} Saturation;

1	30.8	35.2	35.7	39.0	26.5	35.0	27.0	32.9
2	50.0	48.7	42.7	50.0	3.8	53.0	25.3	43.4
3	51.6	50.1	49.0	64.0	26.5	52.3	41.7	47.9
4	49.7	49.4	52.5	57.7	29.4	50.6	49.4	48.4
5	24.3	20.0	25.2	31.2	19.8	23.0	14.7	22.6
6	68.8	70.2	50.4	60.4	65.4	70.7	41.7	61.1
7	58.6	58.6	46.9	64.0	36.8	60.0	34.1	51.3
8	40.2	32.4	25.2	31.2	19.8	38.0	19.4	29.5
9	84.1	69.7	62.3	64.0	65.4	81.8	68.8	70.9
10	50.0	44.1	39.9	41.4	39.7	49.0	27.0	41.6
11	51.8	49.9	52.5	60.0	91.1	97.0	45.9	64.0
12	35.8	38.4	32.2	40.4	29.4	38.0	27.0	34.5
13	70.6	59.4	57.4	60.9	33.9	69.5	65.3	59.6
14	90.8	89.6	72.1	95.0	72.0	98.2	65.3	83.3
15	48.0	49.0	44.8	50.0	44.1	58.1	27.0	45.9
16	30.6	29.2	25.9	30.2	31.6	33.2	14.7	27.9
17	25.4	38.2	37.1	35.0	21.3	49.0	25.3	33.0
18	60.0	59.1	64.4	60.0	31.6	58.0	34.1	52.5
19	30.3	29.7	30.1	20.3	21.3	29.7	12.3	24.8
20	32.4	21.0	30.1	32.3	31.6	41.4	19.4	29.7
21	75.2	60.0	65.8	71.0	68.4	80.2	55.9	68.1
22	8.4	5.4	0.0	0.0	0.0	4.0	0.0	2.5
23	48.3	53.2	44.8	50.0	31.6	56.1	27.0	44.4
24	69.2	67.9	52.5	70.1	47.0	92.1	45.9	63.5
Snd	0.0	0.0	0.0	0.9	0.7	4.0	0.0	0.8

(continued) Appendix J

A Hue;

Stm	A	B	C	D	E	F	G	$\bar{X}$
1	42.4	42.0	52.5	59.3	51.7	50.0	53.7	50.5
2	35,4	38.4	46.0	45.0	43.3	43.7	48.8	42.9
3	40.7	45.0	46.0	52.5	46.0	47.8	50.0	46.9
4	65.3	60.0	59.0	70.0	61.8	56.7	62.5	62.2
5	79.7	83.7	80.0	86.3	88.3	N	N	83.6
6	75.0	75.0	75.0	75.0	75.0	75,0	75.0	75.0
7	40.0	38.4	40.0	45.0	40.8	37.5	41.3	40.4
8	51.4	50.0	56.7	62.5	48.3	49.8	52.5	53.0
9	58.7	65.4	68.0	72.0	70.0	65.0	69.5	66.9
10	40.0	45.0	47.5	54.2	46.8	48.0	50.0	47.4
11	80.3	83.5	81.0	80.0	88.3	80.5	83.7	82.5
12	90.2	95.0	91.3	92.0	90.8	92.7	96.3	92.6
13	46.2	44.8	49.3	53.0	46.8	48.0	50.5	48.4
14	90.3	98.7	94.3	97.0	103.0	97.5	97.5	96.9
15	23.3	32.7	41.3	45.0	45.7	26.3	37.5	36.0
16	82.9	91.3	82.5	80.5	90.0	93.7	107.5	89.8
17	54.5	55.0	53.0	55.0	51.7	51.0	55.0	53.6
18	90.3	90.0	96.0	93.0	97.5	94.8	94.4	93.7
19	14.7	30.7	31.3	50.5	48.3	29.3	45.0	35.7
20	46.3	40.0	52,0	62.5	49.3	51.0	53.7	50.7
21	3.0	7.5	0.6	7.0	8.0	2.3	4.4	4.7
22	78.7	80.0	75.0	75.5	75.0	75.0	77.5	76.7
23	106.3	108.7	109.3	105.5	95.8	106.3	108.7	5.8
24	88.0	86.5	83.0	85.0	92.5	89.3	88.7	87.6
Snd	21.0	20.0	25.0	20.0	N	11.0	20.6	19.6

A Saturations;

Stm	A	B	C	D	E	F	G	$\bar{X}$
1	27.6	28.5	25.2	32.0	40.4	41.0	29.4	32.0
2	38.6	45.1	31.5	32.0	30.9	42.0	31.2	35.9
3	58.0	60.6	51.8	44.0	40.4	54.2	44.1	50.4
4	67.6	73.6	58.8	48.0	44.1	66.9	40.6	57.1
5	11.6	11.1	2.1	22.0	25.7	0.0	0.0	10.4
6	74,5	54.3	56.0	52.0	50.0	80.0	58.8	60.8
7	44.2	37.7	35.7	35.0	19.1	46.0	31.2	35.6
8	23.0	17.5	16.8	26.1	22.1	30.6	21.8	22.6
9	83.7	77.0	72.1	60.9	50.0	53.0	70.0	69.5
10	38.6	31.5	35.7	26.7	37.5	44.1	32.9	35.3
11	92.0	82.8	58.8	48.4	65.4	94.6	47.6	69.9
12	32.0	27.6	16.8	20.7	28.7	21.3	16.5	23.4
13	69.8	69.9	65.1	48.3	47.0	64.0	66.4	61.5
14	89.7	88.6	73.5	57.2	47.0	80.2	55.3	70.2
15	43.0	25.6	32.9	29.1	37.5	40.6	18.2	32.4
16	16.7	17.6	2.1	14.0	22.1	9.0	0.6	11.7
17	36.5	44.7	37.1	27.4	30.9	40.2	32.9	30.5
18	63.9	40.7	39.9	35.0	30.9	55.8	35.3	43.1
19	16.4	9.5	2.1	7.0	44.1	10.0	7.1	13.7
20	21.7	20.3	23.8	15.8	28.7	28.0	21.8	22.9
21	62.5	71.6	63.0	49,0	47.0	63.4	44.1	57.2
22	42.2	39.7	37.8	29.8	12.5	40.9	40.6	34.8
23	32.9	18.9	25.9	15.9	19.1	18.0	12.9	20.5
24	86.9	71.6	65.1	58.0	50.0	84.0	51.7	66.8
Snd	1.4	0.9	0.7	0.7	0.0	7.0	2.9	1.9

Appendix K

Hue and saturation estimates at 200 cd·m^{-2}:

D_{65} Hue;

Stm	A	B	C	D	E	F	G	X̄
1	35.0	34.3	43.7	43.7	39.2	35.0	44.2	39.3
2	32.7	25.0	28.0	30.0	31.7	23.7	17.5	26.9
3	44.7	42.5	27.3	43.7	46.7	43.7	44.7	44.8
4	45.0	50.0	48.5	50.0	44.2	48.7	54.5	48.7
5	5.0	7.7	13.3	2.5	13.3	11.6	5.0	8.3
6	70.0	73.7	78.0	73.7	76.7	73.7	73.5	74.2
7	20.7	18.8	22.5	20.0	25.0	23.7	20.5	21.6
8	31.0	28.7	33.3	43.7	44.2	25.3	33.7	34.3
9	52.3	50.0	55.0	55.0	49.2	48.5	60.0	52.9
10	42.5	35.3	44.5	45.0	46.7	35.0	42.5	41.6
11	90.7	86.8	80.5	82.5	85.8	81.0	80.0	83.9
12	1.7	5.0	4.7	6.3	4.2	2.7	5.0	4.2
13	45.0	49.0	46.7	46.3	45.8	47.0	49.8	47.1
14	97.5	99.3	97.3	97.5	101.7	97.3	98.8	98.5
15	15.7	18.3	18.4	18.7	21.7	19.0	17.0	18.4
16	2.5	5.0	5.5	5.0	5.8	5.3	13.2	6.0
17	42.5	40.0	45.5	45.0	49.2	45.5	51.7	45.6
18	102.5	100.0	98.7	105.0	103.3	100.0	98.7	1.2
19	14.3	10.7	18.3	10.0	4.2	18.7	23.3	14.2
20	18.7	18.7	30.5	41.3	20.8	24.8	37.5	27.5
21	7.5	2.3	3.0	6.3	17.5	1.3	2.0	5.7
22	98.3	97.5	N	N	N	100.0	N	98.6
23	10.0	12.5	11.6	7.5	6.7	12.7	12.5	10.5
24	90.7	95.3	88.4	85.0	92.5	90.5	88.3	90.1
Snd	N	N	N	25.0	N	12.5	N	18.8

D_{65} Saturation;

Stm	A	B	C	D	E	F	G	X̄
1	30.0	32.4	35.7	27.3	32.0	28.7	18.5	29.2
2	32.2	29.7	42.7	35.0	27.1	35.0	21.1	31.8
3	39.5	35.9	49.0	44.8	40.0	35.0	33.4	39.7
4	44.4	48.5	52.5	40.6	46.2	49.7	30.9	44.7
5	16.8	20.6	25.2	22.4	14.0	14.0	6.0	17.0
6	50.0	46.4	50.4	44.8	59.6	53.9	35.4	48.6
7	40.5	44.4	46.9	44.8	32.3	46.2	30.9	40.9
8	26.8	22.7	25.2	22.4	27.0	26.6	16.5	23.9
9	55.5	61.2	62.3	44.8	50.0	59.5	50.4	54.8
10	27.9	32.4	39.9	30.8	40.6	37.1	24.4	33.3
11	57.1	55.9	52.5	42.0	80.3	67.9	35.4	55.9
12	32.6	26.2	32.2	30.8	32.4	23.1	24.0	28.6
13	52.7	46.5	57.4	48.3	50.0	46.2	50.4	50.2
14	68.5	67.3	72.1	66.5	64.2	65.1	61.9	66.5
15	39.4	39.4	44.8	35.0	32.5	39.2	24.0	36.3
16	23.1	20.3	25.9	22.4	23.4	18.9	15.5	21.4
17	27.5	30.0	37.1	24.5	27.7	34.3	21.5	28.9
18	45.1	41.6	64.4	42.0	36.4	42.0	37.4	44.1
19	20.9	24.8	30.1	16.1	36.0	24.5	10.5	23.3
20	27.1	26.0	30.1	22.4	27.1	26.6	13.5	24.7
21	55.2	53.8	65.8	49.7	50.6	53.2	48.4	53.8
22	6.8	0.4	0.0	0.0	0.0	2.8	0.0	1.4
23	38.5	36.0	44.8	35.0	19.5	35.0	24.5	33.3
24	62.7	61.0	52.5	49.7	36.3	60.9	37.4	51.5
Snd	0.0	0.0	0.0	6.3	0.0	4.2	0.0	1.5

(continued) Appendix K

A Hue;

Stm	A	B	C	D	E	F	G	$\bar{X}$
1	43.0	43.0	52.0	55.8	49.3	50.0	53.0	49.4
2	32.0	34.7	46.3	43.3	45.7	39.5	47.0	41.2
3	47.3	44.3	49.3	53.0	48.3	46.3	52.5	48.7
4	65.0	70.2	65.5	6.50	60.0	52.0	60.0	62.5
5	82.5	85.0	80.0	82.5	87.5	87.5	96.3	85.9
6	70.7	75.0	74.9	75.0	75.0	75.0	75.0	74.4
7	42.5	30.7	40.0	43.5	39.5	32.5	40.5	38.5
8	52.5	47.5	55.5	54.3	50.3	50.3	54.5	52.1
9	59.5	55.6	69.5	69.3	69.5	65.0	63.0	64.5
10	44.3	44.3	47.5	53.0	48.0	47.0	50.0	47.7
11	84.7	83.8	79.5	80.5	88.0	79.8	85.0	83.0
12	83.8	90.3	90.5	97.3	85.0	94.7	97.0	92.3
13	47.5	50.5	49.0	45.8	48.0	48.5	50.0	48.4
14	88.0	98.7	97.0	97.0	102.5	90.0	98.5	96.0
15	22.5	32.3	37.0	42.5	41.7	49.0	34.5	37.1
16	85.0	91.3	88.3	86.8	92.0	97.7	101.7	91.8
17	60.0	55.0	56.3	57.0	52.7	50.6	58.0	55.7
18	85.7	88.3	94.5	94.5	98.0	94.5	97.5	93.3
19	15.7	12.7	35.0	56.7	49.0	32.0	46.8	35.4
20	45.0	40.0	51.7	55.7	50.3	48.5	53.0	49.2
21	2.8	11.0	4.5	4.5	7.0	2.5	5.0	5.3
22	82.5	82.5	75.5	77.5	75.0	75.0	77.0	77.9
23	3.7	12.0	9.3	3.0	3.7	7.0	10.0	7.3
24	88.3	87.5	82.5	81.8	90.5	84.5	88.0	86.2
Snd	20.0	21.7	25.0	22.0	12.5	10.5	22.0	19.1

A Saturation;

Stm	A	B	C	D	E	F	G	$\bar{X}$
1	25.6	22.0	29.5	34.9	34.9	22.7	41.2	30.1
2	31.0	33.1	35.5	31.3	31.3	34.6	39.1	33.7
3	53.3	49.3	52.5	51.9	49.2	46.4	61.5	52.0
4	54.6	59.4	53.6	45.6	57.3	54.3	61.5	55.2
5	6.7	8.8	3.4	21.5	26.8	1.0	1.4	9.9
6	55.4	58.1	56.9	60.0	65.3	59.3	72.7	61.1
7	37.1	35.1	34.2	31.3	31.3	31.6	37.7	34.0
8	21.6	25.0	16.1	21.5	23.3	14.8	28.6	21.6
9	62.8	62.8	64.3	51.9	79.7	62.2	94.3	68.3
10	39.8	37.1	34.2	43.0	34.9	31.6	43.3	37.7
11	63.4	64.8	56.3	51.9	82.3	82.0	67.8	66.9
12	23.6	18.2	19.4	26.0	34.9	12.8	14.7	21.4
13	59.4	54.7	58.3	51.9	60.9	64.2	72.7	60.3
14	63.4	60.1	65.7	51.9	60.9	71.1	72.7	63.7
15	30.2	28.4	30.2	23.3	34.9	27.7	21.7	28.1
16	16.6	9.8	2.7	13.4	28.6	4.9	3.5	11.4
17	39.8	34.4	29.5	23.2	45.6	31.6	37.7	34.5
18	40.8	40.5	42.2	39.4	26.8	46.4	43.3	39.9
19	17.0	10.8	2.0	9.8	19.7	7.9	7.0	10.6
20	20.0	20.0	17.4	21.5	15.2	19.8	25.9	20.0
21	48.7	50.0	57.0	45.6	34.9	59.3	52.4	49.7
22	35.3	40.7	44.9	29.5	11.6	36.6	46.1	35.0
23	8.3	15.6	19.4	19.7	8.1	11.9	19.6	14.7
24	68.4	54.9	53.6	52.8	71.6	74.1	58.7	62.0
Snd	0.9	1.2	0.7	8.0	3.6	4.0	1.4	2.8

Appendix L

Hue and saturation estimates with dark adaptation:

Hue;

Stimulus	A	C	E	$\bar{X}$
1	30.4	35.0	43.4	36.3
2	29.2	27.3	25.0	27.2
3	34.3	44.3	45.7	41.4
4	50.0	48.7	50.0	49.6
5	17.8	21.3	18.3	19.1
6	72.3	75.5	75.0	74.1
7	18.0	20.0	24.3	20.8
8	25.0	25.0	N	25.0
9	60.5	55.3	52.7	56.2
10	39.3	35.0	37.3	37.2
11	85.0	90.0	80.7	85.2
12	6.7	7.5	9.7	8.0
13	46.3	40.3	43.0	43.2
14	98.3	102.3	100.0	0.2
15	20.0	17.7	18.3	18.7
16	12.7	10.3	11.0	11.3
17	40.0	38.3	44.7	41.0
18	100.0	100.0	100.0	100.0
19	7.0	9.3	5.3	7.2
20	25.0	26.3	28.0	26.4
21	6.0	8.3	3.3	5.9
22	62.5	73.7	N	68.1
23	12.5	13.0	14.3	13.3
24	93.3	95.0	88.7	92.3

Saturations;

1	30	31	11	24.0
2	50	43	64	52.3
3	35	37	36	36.0
4	40	46	23	36.3
5	15	18	11	14.7
6	40	48	23	37.0
7	35	48	36	39.7
8	15	25	0	13.3
9	60	59	50	56.3
10	28	37	11	25.3
11	55	64	50	56.3
12	29	31	11	23.7
13	40	48	23	37.0
14	60	64	50	58.0
15	55	54	64	57.7
16	10	14	1	8.3
17	25	31	5	20.7
18	35	43	11	29.7
19	20	31	11	20.7
20	20	21	0	13.7
21	75	70	78	74.3
22	5	6	0	3.7
23	30	34	23	29.0
24	55	54	64	57.7

Appendix M

Corresponding chromaticities for 4 adaptation conditions:

D_{65};

Sat.		R	YR	Y	YG	G	BG	B	BR
20	u'	.218	.215	.208	.199	.185	.182	.189	.207
	v'	.474	.492	.495	.493	.480	.465	.453	.457
40	u'	.267	.249	.226	.196	.151	.144	.171	.226
	v'	.486	.534	.543	.543	.498	.454	.412	.427
60	u'	.321	.273	.233	.191	.120	.111	.157	.243
	v'	.497	.555	.566	.570	.512	.442	.371	.401
80	u'	.405	-	-	-	.090	.082	.140	.270
	v'	.507	-	-	-	.522	.430	.295	.355
100	u'	.484	-	-	-	.045	.045	-	.286
	v'	.511	-	-	-	.534	.408	-	.326

D_{44};

Sat.		R	YR	Y	YG	G	BG	B	BR
20	u'	.232	.235	.224	.211	.196	.188	.196	.222
	v'	.486	.503	.508	.505	.493	.478	.463	.473
40	u'	.272	.269	.245	.210	.169	.155	.174	.246
	v'	.492	.528	.541	.539	.507	.467	.418	.445
60	u'	.332	-	-	.204	.138	.113	.152	.473
	v'	.497	-	-	.569	.521	.453	.363	.409
80	u'	.420	-	-	-	.098	.080	.137	.307
	v'	.502	-	-	-	.535	.441	.304	.350
100	u'	.508	-	-	-	.054	.045	-	-
	v'	.502	-	-	-	.545	.445	-	-

A ;

Sat.		R	YR	Y	YG	G	BG	B	BR
20	u'	.278	.281	.269	.258	.243	.235	.232	.267
	v'	.528	.541	.543	.539	.531	.523	.500	.516
40	u'	.316	.315	.281	.258	.227	.211	.205	.286
	v'	.529	.554	.560	.555	.538	.520	.468	.491
60	u'	.366	-	-	-	.195	.166	.179	.303
	v'	.530	-	-	-	.548	.508	.424	.452
80	u'	.413	-	-	-	.150	.117	-	-
	v'	.528	-	-	-	.556	.486	-	-

(continued)

Dark adaptation;

Sat.		R	YR	Y	YG	G	BG	B	BR
10	u'	.238	.230	.212	.200	.183	.178	.185	.227
	v'	.454	.470	.472	.470	.456	.433	.412	.418
20	u'	.298	.277	.228	.192	.148	.142	.166	.250
	v'	.477	.515	.533	.529	.480	.423	.377	.395
40	u'	.390	.316	.237	.189	.100	.103	.141	.279
	v'	.498	.546	.561	.568	.508	.414	.327	.363
60	u'	.481	-	-	-	.062	.064	.122	.316
	v'	.508	-	-	-	.525	.402	.283	.313

VIII. References

1. J. Aitken (1873), "Colour and colour sensation", Trans.Roy.Scot.Soc.Arts, 8:375-418.

2. M. Alpern and H. David (1959), "The additivity of contrast in the human eye", J.Gen.Physiol., 43:109-126.

3. N.H. Anderson (1971), "Integration theory and attitude change", Psychol.Rev., 78:171-206.

4. F. Attneave (1959), Applications of Information Theory to Psychology: A Summary of Basic Concepts, Methods, and Results, New York, Holt.

5. F. Attneave (1962), "Perception and related areas", (pp.619-659) in: S. Koch (ed), Psychology: A Study of A Science, Vol. 4, New York, McGraw-Hill.

6. H. Aubert (1865), Physiologie de Netzhaut, Breslau, Morganstern.

7. L.L. Avant (1965), "Vision in the Ganzfeld", Psychol.Bull., 64:246-258.

8. H.D. Baker (1953), "The instantaneous threshold and early dark adaptation", J.Opt.Soc.Amer., 43:798-803.

9. M.M. Balcon (1970), "Influence of red and blue pre-adaptation on hue matching of purple samples", J.Opt.Soc.Amer., 60:118-121.

10. H.B. Barlow (1957), "Increment thresholds at low intensities considered as signal/noise discriminations", J.Physiol., 136:469-488.

11. A.C. Barr, C.N. Clark and J. Hessler (1952), "Evaluation of color rendition by fluorescent lamps - an explanatory study", Ill.Eng., 47:649-658.

12. C.J. Bartleson (1958), "Influence of observer adaptation on the acceptance of color prints", Phot.Sci.Eng., 2:32-39.

13. C.J. Bartleson (1960), "Memory-colors of familiar objects", J.Opt.Soc.Amer., 50:73-77.

14. C.J. Bartleson (1961), "Color in memory in relation to photographic reproduction", Phot.Sci.Eng., 5:327-331.

15. C.J. Bartleson (1966), "Color-appearance measurement. I. A colorimeter for haploscopic matching", Phot.Sci.Eng., 10:104-110.

16. C.J. Bartleson (1968a) ,"Pupil diameters and retinal illuminances in interocular brightness matching", J.Opt.Soc.Amer., 58:853-855.

17. C.J. Bartleson (1968b), "Color perception and color television", J.Soc.Mot.Pict.Tel.Eng., 77:1-12.

18. C.J. Bartleson (1972), "Color: A nominal definition", J.Color & Appear., 1:31-45.

19. C.J. Bartleson (1976), "Brown", J.Color Res.Appl., 1: (in press).

20. C.J. Bartleson and E.J. Breneman (1967a), "Brightness pereption in complex fields", J.Opt.Soc. Amer., 57:953-957.

21. C.J. Bartleson and E.J. Breneman (1967b), "Brightness reproduction in the photographic process", Phot.Sci.Eng., 11:254-262.

22. C.J. Bartleson and E.J. Breneman (1973), "Differences among responses of observers in scaling brightness", Die Farbe, 22:200-212.

23. C.J. Bartleson and R.F. Witzel (1967), "Illumination for color transparencies", Phot.Sci.Eng., 11:329-335.

24. W.S. Battersby and I.W. Wagman (1959), "Neural limitations of visual excitability, I.: The time course of monocular light adaptation", J.Opt.Soc.Amer., 49:752-759.

25. J. Beck (1959), "Stimulus correlates for the judged illumination of a surface", J.Exp. Psychol., 58:267-274.

26. J. Beck (1972), Surface Color Perception, Ithaca (New York), Cornell University Press.

27. R. Belsey (1964), "Color perception and the Land two-color projections", J.Opt.Soc.Amer., 54:529-531.

28. G. Bénéze (1929), "Notes sur la loi de Fechner", Rev.Phil., 108:429-432.

29. P. Berman and H.W. Leibowitz (1965), "Some effects of contour on simultaneous brightness contrast", J.Exp.Psychol., 69:251-256.

30. D. Bernoulli (1738), "Specimen theoriae novae de mensura sortis", Concentarii Academiae Scientiarum Imperiales Petopolotanae, 5:175-192.

31. B. Bond and S.S. Stevens (1969), "Cross-modality matching of brightness to loudness by 5-year-olds", Percept.Psychophys., 6:337-339.

32. E.G. Boring (1942), Sensation and Perception in the History of Experimental Psychology, New York, Appleton-Century-Crofts.

33. P. Bouguer (1760), Traité d'optique sur la gradation de la lumière, Paris, Claude Tombert.

34. P.J. Bouma and A.A. Kruithoff (1947), "Die chromatische Anpassung des Auges", Philips Tech. Rev., 9:257-263.

35. M.A. Bouman (1952), "Peripheral contrast thresholds for various and different wavelengths for adapting field and test stimulus", J.Opt.Soc. Amer., 42:820-831.

36. M.A. Bouman (1955), "On foveal peripheral interaction in binocular vision", Optica Acta, 1:177-183.

37. R.M. Boynton (1956), "Rapid chromatic adaptation and the sensitivity functions of human color vision", J.Opt.Soc.Amer., 46:172-179.

38. R.M. Boynton (1958), "On-responses in the visual system as inferred from psychophysical studies of rapid-adaptation", Arch.Ophthal., 60:800-810.

39. R.M. Boynton (1975), "Color, hue, and wavelength", (pp.301-347) in: E.C. Carterette and M.P. Friedman (eds), Handbook of Perception. Vol. V. Seeing, New York, Academic Press.

40. R.M. Boynton, W.R. Bush and J.M. Enoch (1954), "Rapid changes in foveal sensitivity resulting from direct and indirect adapting stimuli", J.Opt.Soc.Amer., 44:56-60.

41. R.M. Boynton, S.R. Das and J. Gardiner (1966), "Interactions between photopic visual mechanisms revealed by mixing conditioning fields", J.Opt.Soc.Amer., 56:1775-1780.

42. R.M. Boynton and J. Gordon (1965), "Bezold-Brücke hue shift measured by color-naming technique", J.Opt.Soc.Amer., 55:78-85.

43. R.M. Boynton, M. Ikeda and W.S. Stiles (1964), "Interactions among chromatic mechanisms as inferred from positive and negative increment thresholds", Vis.Res., 4:87-117.

44. R.M. Boynton, H. Scheibner, T. Yates and E. Rinalduci (1965), "Theory and experiments concerning the heterochromatic threshold-reduction factor (HTRF)", J.Opt.Soc.Amer., 55:1672-1685.

45. R.M. Boynton and D.N. Whitten (1970), "Visual adaptation in monkey cones: Recordings of late re-

ceptor potentials", Science, _170_:1423-1426.

46. E.J. Breneman (1958), "Dependence of luminance required for constant brightness upon chromaticity and chromatic adaptation", J.Opt.Soc. Amer., _48_:228-232.

47. E.J. Breneman (1966), "Color appearance measurement. II. A haploscopic brightness meter", Phot,Sci.Eng., _10_:144-149.

48. E.J. Breneman (1976), "Perceived saturation in complex stimuli viewed in light and dark surrounds", J.Opt.Soc.Amer., _66_: (in press).

49. F. Brentano (1874), _Psychologie vom empirischen Standpunkte_, Leipzig, Duncker and Humblot.

50. W.L. Brewer (1954), "Fundamental response functions and binocular color matching", J.Opt. Soc.Amer., _44_:207-212.

51. D. Brewster (1831), "Newton's 1691 letter to Locke. I. Experiments on ocular spectra produced by the action of the sun's light on the retina", Edinborough J.Sci., _4_:75-77.

52. P.W. Bridgman (1927), _The Logic of Modern Physics_, New York, Macmillan; pp.33-36.

53. G.S. Brindley (1953), "The effects on colour vision of adaptation to very bright lights", J.Physiol.(London), _122_:332-350.

54. G.S. Brindley (1954), "The summation areas of human colour-receptive mechanisms at increment threshold", J.Physiol.(London), _124_: 400-408.

55. G.S. Brindley (1970), _Physiology of the Retina and Visual Pathway, Second Edition_, London, E. Arnold.

56. A. Broca (1894), "Etudes théoretiques et expérimentales sur les sensations visuelles et la photométrie", J.Phys.Radium, _3_:206-218.

57. P.K. Brown and G. Wald (1964), "Visual pigments in single rods and cones of the human retina", Science, _144_:45-52.

58. G.J. Burch (1898), "An artificial temporary colourblindness with examination of the colour sensations of 109 persons", Proc.Roy.Soc.(London), _63_:35-38.

59. R.W. Burnham (1959), "Predictions of shifts in color appearance with a change from daylight to tungsten adaptation", J.Opt.Soc.Amer., 49:254-263.

60. R.W. Burnham, R.M. Evans and S.M. Newhall (1952), "Influence on color perception of adaptation to illumination", J.Opt.Soc.Amer., 42:597-605.

61. R.W. Burnham, R.M. Evans and S.M. Newhall (1957), "Prediction of color appearance with different adaptation illuminations", J.Opt.Soc. Amer., 47:35-42.

62. R.W. Burnham, R.M. Hanes and C.J. Bartleson (1963), Color: A Guide to Basic Facts and Concepts, New York, J. Wiley.

63. N.R. Campbell (1928), An Account of the Principles of Measurement and Calculation, London, Longmans.

64. N.R. Campbell (1938), Symposium: Measurement and its Importance for Philosophy, Aristotelian Society Supplement, Vol. 17, London, Harrison.

65. W.B. Cannon (1939), The Wisdom of the Body, Second Edition, New York, Norton.

66. C.M. Cicerone, D.H. Krantz and J. Larimer (1975), "Opponent-process additivity - III. Effect of moderate chromatic adaptation", Vis.Res., 15:1125-1135.

67. A.L.A. Comrey (1950), "Proposed method for absolute ratio scaling", Psychometrika, 15:317-325.

68. C.H. Coombs, R.M. Dawes and A. Tversky (1970), Mathematical Psychology, Englewood Cliffs (New Jersey), Prentice-Hall.

69. B.H. Crawford (1947), "Visual adaptation in relation to brief conditioning stimuli", Proc. Roy.Soc.(London), 134B:283-302.

70. H.J.A. Dartnall (1972), Handbook of Sensory Physiology, Vol. VII/1, Photochemistry of Vision, Berlin, Springer.

71. R.W. Darwin (1786), "New experiments on the ocular spectra of light and colours", Phil.Trans., 76(Pt.1):313-348.

72. J.R.L. Delboeuf (1873), "Etude psychophysique: Recherches théoretiques et expérimentales sur la mesure des sensations, et spécialement des sensations de lumière et de fatigue", Mem.Acad.Roy.Belg., 23:No.5 (issue).

73. R. DeValois (1965), "Analysis and coding of color vision in the primate visual system", Cold Springs Harbor Symposium, 30:567-579.

74. A.L. Diamond (1953), "Foveal simultaneous brightness contrast as a function of inducing- and test-field luminances", J.Exp.Psychol., 45:304-314.

75. A.L. Diamond (1955), "Foveal simultaneous contrast as a function of inducing area", J.Exp. Psychol., 50:144-152.

76. A.L. Diamond (1962a), "Simultaneous contrast as a function of test-field area", J. Exp. Psychol., 64:336-345.

77. A.L. Diamond (1962b), "Brightness of a field as a function of its area", J.Opt.Soc.Amer., 52:700-706.

78. F.L. Dimmick (1956), "Specifications and calibration of the 1953 edition of the Inter-Society Color Council aptitude test", J.Opt.Soc.Amer., 46:389-393.

79. F.L. Dimmick and M.R. Hubbard (1939a), "The spectral location of psychologically unique yellow, green, and blue", Amer.J.Psychol., 52:242-254.

80. F.L. Dimmick and M.R. Hubbard (1939b), "The spectral components of psychologically unique red", Amer.J.Psychol., 52:348-353.

81. F.L. Dimmick and R.E. Wienke (1958), "How red is red?", Amer.J.Psychol., 71:298-304.

82. J.E. Dowling (1967), "The site of visual adaptation", Science, 155:273-279.

83. J.E. Dowling, D. Green, H. Ripps and I. Siegel (1973), "Non-receptor adaptation in the skate retina", presented to the Association for Research in Vision and Ophthalmology, Sarasota, Florida, April 1973.

84. J.E. Dowling and H. Ripps (1972), "Adaptation in skate photoreceptors", J.Gen.Physiol., 60:698-719.

85. A.A. Eastman and G.A. Brecher (1972), "The subjective measurement of color shifts with and without chromatic adaptation", J.Ill.Eng.Soc.(USA), 1:239-244.

86. G. Ekman (1956), "Subjective power functions and the method of fractionation", Report No. 34 of the Psychological Laboratory, University of Stockholm.

87. C. Enroth-Cugell and R.M. Shapley (1973), "Flux, not retinal illumination is what cat retinal ganglion cells really care about", J.Physiol., 233:311-326.

88. R.M. Evans (1943), "Visual processes and color photography", J.Opt.Soc.Amer., 33:579-590.

89. R.M. Evans (1948), Introduction to Color, New York, J. Wiley.

90. R.M. Evans (1959a), "Fluorescence and gray content of surface colors", J.Opt.Soc.Amer., 49:1049-1059.

91. R.M. Evans (1959b), Eye, Film, and Camera in Color Photography, New York, J. Wiley.

92. R.M. Evans (1964), "Variables of perceived color", J.Opt.Soc.Amer., 54:1467-1474.

93. R.M. Evans (1974), The Perception of Color, New York, J. Wiley.

94. R.M. Evans and B.K. Swenholt (1967), "Chromatic strength of colors: Dominant wavelength and purity", J.Opt.Soc.Amer., 57:1319-1324.

95. R.M. Evans and B.K. Swenholt (1968), "Chromatic strength of colors, part II. The Munsell system", J.Opt.Soc.Amer., 58:580-584.

96. R.M. Evans and B.K. Swenholt (1969), "Chromatic strength of colors, III. Chromatic surrounds and discussion", J.Opt.Soc.Amer., 59:628-634.

97. S. Exner (1868), "Ueber einige neue subjektive Gesichtserscheinungen", Arch.ges.Physiol., 1:375-394.

98. G.T. Fechner (1860/1966), Elemente der Psychophysik, Leipzig, Breitkopf and Härtel; translated as: Elements of Psychophysics, Vol. I., H.E. Adler translator, D.H. Howes and E.G. Boring editors, New York, H. Holt, 1966.

99. A. Ferguson (1940), "Final report on quantitative estimates of sensory events", Adv. in Sci., 2:331-349.

100. A. Fiorentini and T. Radici (1958), "Effect of illumination of one eye on the apparent brightness of a field seen by the other eye", Istituto Nazionale di Ottica, Arcetri-Firenze, Final Report on Contract Number AF61(052)17.

101. R.A. Fischer and F. Yates (1953), Statistical Tables, Fourth Edition, Edinburgh, Oliver and Boyd.

102. J. Fraunhofer (1815), "Bestimmung des Brechungs- und Farbenzerstreuungs-Vermögens verschiedener Glasarten, in Bezug auf die Vervolkommung achromatischer Fernröhre", Denkschr.

Acad.Wiss.München (math. naturwiss.Cl.) 5:193-226.

103. G.A. Fry (1931), "The stimulus correlates of bulky color", Amer.J.Psychol., 43:618-620.

104. G.A. Fry (1955), "Chromatic adaptation and the red and green fundamental stimuli", Die Farbe, 4:175-181.

105. G.A. Fry (1958), "Chromatic adaptation with special reference to the blue-green region of the colour-mixture diagram", (pp.665-680) in: Visual Problems of Colour, II., London, H.M. Stationery Office.

106. G.A. Fry (1964), "Measurement, specification, and prediction of transient states of adaptation", Ill.Eng.(USA), 59:453-460.

107. G.S. Fullerton and J. McK. Cattell (1892), On the Perception of Small Differences, Philadelphia, University of Pennsylvania Press.

108. F.H. Gage (1934), "An experimental investigation of the measurability of visual sensation", Proc.Roy.Soc.(London), 116B:123-128.

109. A. Gelb (1929), "Die Farbenkonstanz der Sehdinge", (pp.594-678) in: A. Bethe (ed), Handbuch der normalen und pathologischen Physiologie, Berlin, Springer.

110. E. Gellhorn and G. Fabian (1926), "Über den Einfluss der farbigen Umstimmung des Auges auf die Unterschiedsschwelle für Farbenintensitäten", Pflügers Arch.ges.Physiol., 214:274-294.

111. J.J. Gibson, J. Purdy and L. Lawrence (1955), "A method of controlling stimulation for the study of space perception: The optical tunnel", J.Exp.Psychol., 50:1-14.

112. C.H. Graham and J.L. Brown (1965), "Color contrast and color appearances: Brightness constancy and color constancy", (pp.452-478) in: C.H. Graham (ed), Vision and Visual Perception, New York, Wiley.

113. R. Granit (1962), "The visual pathway. A confrontation of physiology with anatomy", (pp.661-667) in: H. Davson (ed), The Eye, Vol. 2, The Visual Process, New York, Academic Press.

114. R. Granit and G. Svaetichin (1938), "Principles and techniques of electrophysiological analysis of colour perception with the aid of micro-electrodes", Upsala Läk Fören Forh., 65:161-177.

115. R. Granit and P.O. Therman (1938), "The 'slow potentials' associated with excitation and inhibition in the excised eye", J.Physiol. (London), 93:9P.

116. H. Grassman (1853), "Zur Theorie der Farbenmischung", Poggendorf.Ann.Phys., 89:69-79.

117. H. Grassman (1854), "On the theory of compound colours", Phil.Mag., 7:254-264.

118. J.P.A. Guilford (1932), "A generalized psychophysical law", Psychol.Rev., 39:73-85.

119. S.L. Guth and H.R. Lodge (1973), "Heterochromatic additivity, foveal sensitivity, and a new color model", J.Opt.Soc.Amer., 63:450-462.

120. T. Haack (1929), "Kontrast und Transformation", Z.Psychol., 112:93-138.

121. S. Hecht (1928), "On the binocular fusion of colors and its relation to theories of color vision", Proc.Nat.Acad.Sci.(Washington), 14:237-245.

122. S. Hecht (1934), "The nature of the photoreceptor process", in: C. Murchison (ed), Handbook of General Experimental Psychology, Worcester, Massachusetts, Clark University Press.

123. P. Heggelund (1974), "Achromatic color vision - II: Measurement of simultaneous achromatic achromatic contrast within a bidimensional system", Vis.Res., 14:1081-1088.

124. E.G. Heinemann (1955), "Simultaneous brightness induction as a function of inducing- and test-field luminances", J.Exp.Psychol., 50:89-96.

125. E.G. Heinemann (1972), "Simultaneous brightness induction", (pp.146-169) in: D. Jameson and L.M. Hurvich (eds), Handbook of Sensory Physiology, Vol. VII/4, Visual Psychophysics, Berlin, Springer.

126. H. von Helmholtz (1866), "Die Lehre von den Gesichtsempfindungen", in: W. Nagel (ed) Handbuch der Physiologische Optik, II., Leipzig, Voss.

127. H. von Helmholtz (1887), "Zählen und Messen erkenntnisstheoretisch betrachtet", (pp. 17-52) in: E. Zeller (ed), Philosophische Aufspätze, Laipzig, Fues Verlag.

128. H. von Helmholtz (1925), Helmholtz's Treatise on Physiological Optics (J.P. Southall, ed),

New York, Optical Society of America.

129. H. von Helmholtz (1962), "The recent progress of the theory of vision - 1868", in: M. Kline (ed), Popular Scientific Lectures, New York, Dover.

130. A. Helms and R. Prehn (1958), "Empfindlichkeitsänderungen des dunkeladaptierten menschlichen Auges bei monocularer Adaptation in Abhängigkeit vom Helladaptationsniveau", v.Grafes Arch.Ophthal., 160:285-289.

131. A. Helms and J. Raeuber (1958), "Über Empfindlichkeitsänderungen des monocular dunkeladaptierten Auges bei verschiedenfarbiger Helladaptation des anderen Auges", v.Grafes Arch.Ophthal., 160:290-292.

132. H. Helson (1938), "Fundamental problems in color vision. I. The principle governing changes in hue, saturation and lightness of non-selective samples in chromatic illumination", J.Exp.Psychol., 23:439-476.

133. H. Helson (1943), "Some factors and implications of color constancy", J.Opt.Soc.Amer., 33: 555-567.

134. H. Helson (1963), "Studies of anomalous contrast and assimilation", J.Opt.Soc.Amer., 53: 179-184.

135. H. Helson (1964), Adaptation-Level Theory, New York, Harper and Row.

136. H. Helson and J. Grove (1947), "Changes in hue, lightness and saturation of surface colors in passing from daylight to incandescent-lamp light", J.Opt.Soc.Amer., 37:387-395.

137. H. Helson and V.B. Jeffers (1940), "Fundamental problems in color vision. II. Hue, lightness and saturation of selective samples in chromatic illumination", J.Exp.Psychol., 26:1-27.

138. H. Helson, D.B. Judd and M.H. Warren (1952), "Object-color changes from daylight to incandescent filament illumination", Ill.Eng., 47:221-233.

139. H. Helson, D.B. Judd and M. Wilson (1956), "Color rendition with fluorescent sources of illumination", Ill.Eng., 51:329-346.

140. H. Helson and W.C. Michels (1948), "The effect of chromatic adaptation on achromaticity", J.Opt.Soc.Amer., 38:1025-1032.

141. H. Helson and F.H. Rohles (1959), "A quantitative study of reversal of classical lightness con-

trast", Amer.J.Psychol., 72:530-538.

142. J.F. Herbart (1824), Psychologie als Wissenschaft, Königsberg, Unger (p.3).

143. E. Hering (1874), Grundzüge der Lehre vom Lichtsinn, Berlin, Springer.

144. E. Hering (1888), "Über die von v.Kries wider die Theorie der Gegenfarbe erhobenen Einwände", Pflüges Arch.f.Physiol., 62:123-133.

145. E. Hering (1964), Outlines of a Theory of the Light Sense - 1874, (translated by L.M. Hurvich and D. Jameson) Cambridge (Massachusetts), Harvard University Press.

146. H.L. Hollingworth (1909), "The inaccuracy of movement", Arch.Psychol., No.13, issue.

147. D.C. Hood and P.A. Hock (1975), "Light adaptation of the receptors: Increment threshold functions for the frog's rods and cones", Vis.Res., 15:545-553.

148. D.H. Hubel and T.N. Wiesel (1959), "Receptive fields of single neurones in the cat's striate cortex", J.Physiol., 148:574-591.

149. D.H. Hubel and T.N. Wiesel (1961), "Integrative action in the cat's lateral geniculate body", J.Physiol., 155:385-398.

150. D.H. Hubel and T.N. Wiesel (1962), "Receptive fields, binocular interaction and fundamental architecture in the cat's visual cortex", J.Physiol., 160:106-154.

151. D.H. Hubel and T.N. Wiesel (1968), "Receptive fields and functional architecture of monkey striate cortex", J.Physiol., 195:215-243.

152. R.W.G. Hunt (1949), "Visual adaptation and the apparent saturation of colours", Proc. Phys.Soc.(London), 62B:203.

153. R.W.G. Hunt (1950), "The effect of daylight and tungsten light-adaptation on color perception", J.Opt.Soc.Amer., 40:362-371.

154. R.W.G. Hunt (1952), "Light and dark adaptation and the perception of color", J.Opt.Soc. Amer., 42:190-199.

155. R.W.G. Hunt (1953), "The perception of color in 1^{o} fields for different states of adaptation", J.Opt.Soc.Amer., 43:479-484.

156. R.W.G. Hunt (1958), "Adaptation and trichromatic theory", (pp.640-664) in: Visual Problems

of Colour, Symposium No.8, London, H.M. Stationery Office.

157. R.W.G. Hunt (1965), "Measurement of color appearance", J.Opt.Soc.Amer., 55:1540-1551.

158. R.W.G. Hunt (1975), The Reproduction of Colour, Third Edition, London, Fountain Press.

159. R.W.G. Hunt (1976), "The specification of colour appearance" (private communication).

160. R.W.G. Hunt and L.M. Winter (1975), "Colour adaptation in picture-viewing situations", J.Phot.Sci., 23:112-115.

161. L.M. Hurvich and D. Jameson (1951a), "A psychophysical study of white. I. Neutral adaptation", J.Opt.Soc.Amer., 41:521-529.

162. L.M. Hurvich and D. Jameson (1951b), "A psychophysical study of white. II. Adaptation as variant", J.Opt.Soc.Amer., 41:787-796.

163. L.M. Hurvich and D. Jameson (1954), "Spectral sensitivity of the fovea. III. Heterochromatic brightness and chromatic adaptation", J.Opt.Soc.Amer., 44:213-222.

164. L.M. Hurvich and D. Jameson (1955), "Some quantitative aspects of an opponent-colors theory. II. Brightness, saturation, and hue in normal and dichromatic vision", J.Opt.Soc.Amer., 45:602-616.

165. L.M. Hurvich and D. Jameson (1958), "Further development of a quantified opponent-colours theory", (pp.691-723) in: Visual Problems of Colour. II, London, H.M. Stationery Office.

166. L.M. Hurvich and D. Jameson (1960), "Perceived color, induction effects, and opponent-response mechanisms", J.Gen.Physiol., 43S:63-80.

167. L.M. Hurvich and D. Jameson (1961), "Opponent chromatic induction and wavelength discrimination", (pp.144-152) in: R. Jung and H. Kornhuber (eds), Neurophysiology and Psychophysics, Berlin, Springer.

168. T. Indow (1961), "An example of motivation research applied to product design" (private communication).

169. T. Indow (1974), "Scaling of saturation and hue shift: Summary of results and implications", (pp.351-362) in: H.R. Moskowitz (ed), Sensation and Measurement, Dordrecht, D. Reidel.

170. T. Indow and S.S. Stevens (1966), "Scaling saturation and hue", Percept.Psychophys., 1:253-271.

171. C.R. Ingling, Jr. and B.A. Drum (1973), "How neural adaptation changes chromaticity coordinates", J.Opt.Soc.Amer., 63:369-373.

172. I.G.H. Ishak, H. Bouma and H.J.J. Bussel (1970), "Subjective estimates of colour attributes for surface colours", Vis.Res., 10:489-500.

173. R.E. Jaensch (1921), "Über den Farbenkontrast und die sog. Berücksichtigung der farbigen Beleuchtung", Z.Sinnesphysiol., 52:165-180.

174. R.E. Jaensch and E.A. Müller (1919), "Über die Wahrnehmung farbloser Helligkeiten und den Helligkeitskontrast", Z.Psychol., 83:266-341.

175. W. James (1890), Principles of Psychology, New York, H. Holt.

176. D. Jameson (1972), "Theoretical issues of color vision", (pp.381-412) in: D. Jameson and L.M. Hurvich (eds), Handbook of Sensory Physiology, Vol.VII/4, Visual Psychophysics, Berlin, Springer.

177. D. Jameson and L.M. Hurvich (1955), "Some quantitative aspects of an opponent-colors theory. I. Chromatic responses and spectral saturation", J.Opt.Soc.Amer., 45:546-552.

178. D. Jameson and L.M. Hurvich (1956), "Some quantitative aspects of opponent-colors theory. III. Changes in brightness, saturation and hue with chromatic adaptation", J.Opt.Soc.Amer., 46:405-415.

179. D. Jameson and L.M. Hurvich (1959), "Perceived color and its dependence on focal, surrounding, and preceeding stimulus variables", J.Opt.Soc.Amer., 49:890-898.

180. D. Jameson and L.M. Hurvich (1961), "Opponent chromatic induction: Experimental evaluation and theoretical account", J.Opt.Soc. Amer., 51:46-53.

181. D. Jameson and L.M. Hurvich (1964), "Theory of brightness and color contrast in human vision", Vis.Res., 4:135-154.

182. D. Jameson and L.M. Hurvich (1968), "Opponent-response functions related to measured cone photopigments", J.Opt.Soc.Amer., 58:429-430.

183. D. Jameson and L.M. Hurvich (1972), "Color adaptation: Sensitivity, contrast, after-images", (pp.568-581) in: D. Jameson and L.M. Hurvich (eds), Handbook of Sensory Physiology, Vol.VII/4, Visual Psychophysics, Berlin, Springer.

184. J. Jastrow (1887), "The psycho-physic law and star magnitude", Amer.J.Psychol., 1:112-127.

185. L.A. Jones and H.R. Condit (1941), "The brightness scale of exterior scenes and computation of correct photographic exposure", J. Opt.Soc.Amer., 31:651-673.

186. D.B. Judd (1940), "Hue, saturation and lightness of surface colors with chromatic illumination", J.Opt.Soc.Amer., 30:2-32.

187. D.B. Judd (1951), "Basic correlates of the visual stimulus", (pp.811-867) in: S.S. Stevens (ed), Handbook of Experimental Psychology, New York, Wiley.

188. D.B. Judd (1960), "Appraisal of Land's work on two-primary color projections", J.Opt.Soc. Amer., 50:254-267.

189. D.B. Judd (1961), "A five-attribute system of describing visual appearance", ASTM Special Technical Publication No. 297.

190. D.B. Judd and G. Wyszecki (1975), Color in Business, Science, and Industry, 3rd Edition, New York, Wiley.

191. R. Jung (1961), "Korrelation von Neuronentätigkeit un Sehen", (pp.410-434) in: R. Jung and H. Kornhuber (eds), The Visual System, Berlin, Springer.

192. P.K. Kaiser and J.P. Comerford (1975), "Flicker photometry of equally bright lights", Vis. Res., 15:1399-1402.

193. P.K. Kaiser, J.P. Comerford and P.A. Biggin (1974), "Least purity difference perceptible near spectrum locus as a function of wavelength", J.Opt.Soc.Amer., 64:1386.

194. P.K. Kaiser, J.P. Comerford and D.B. Bodinger (1976), "Saturation of spectral lights", J.Opt.Soc.Amer., 66:818-826.

195. P.K. Kaiser, P.A. Herzberg and R.M. Boynton (1971), "Chromatic border distinctness and its relation to saturation", Vis.Res., 11:953-968.

196. P.K. Kaiser and J.A.S. Kinney (1975), "Problems with heterochromatic photometry", Report No. 6 of York University Department of Psychology (Toronto, Ontario); 17 pages.

197. P.K. Kaiser and P. Smith (1972), "Minimally distinct borders as a criterion in visual photometry", Compte rendu CIE, 21A:147-149.

198. G. Kanizsa (1969), "Perception, past experience and the impossible experiment", Acta Psychologica, 31:66-96.

199. W.E. Kappauf (1975), "Regression effect in judgments to determine equal response contours", Percept.Psychophys., 17:405-410.

200. L. Kardos (1928), "Dingfarbenwahrnehmung und Duplizitätstheorie", Z.Psychol., 108:240-314.

201. D. Katz (1911), "Die Erscheinungsweisen der Farben un Ihre Beeinflussing durch die individuelle Erfahrung", Z.Psychol., 7:315-332; Ergänzungsband.

202. D. Katz (1930), Der Aufbau der Farbwelt, Leipzig, Barth.

203. D. Katz (1935), The World of Colour, (translated by R.B. MacLeod and C.W. Fox), London, Kegan Paul, Trench, Trubner.

204. C. Kellersohn (1955), "Adaptation chromatique et lumière blanche", Die Farbe, 4:159-165.

205. P.E. King-Smith and D. Carden (1976), "Luminance and opponent-color contributions to visual signal detection and adaptation and to temporal and spatial integration", J.Opt.Soc. Amer., 66:709-717.

206. A. Kirschmann (1891), "Ueber die quantitativen Verhältnissen des simultanen Helligkeits- und Farbenkontrastes", Psychol.Stud., 6: 417-491.

207. K. Koffka (1935), Principles of Gestalt Psychology, New York, Harcourt Brace.

208. K. Koffka and M.R. Harrower (1931), "Color and organization", Psychol.Forsch., 15:145-192.

209. I. Kohler (1962), "Experiments with goggles", Sci.Amer., 206:2-12.

210. A. König (1886), "Die Grundempfindungen und ihre Intensitäts-Vertheilung im Spectrum", Sitz. Akad.Wiss. Berlin, (1886):805-829.

211. A. König and C. Dieterici (1893), "Die Grundempfindungen in normalen und anomalen Farben Systemen und ihre Intensitäts-Verteilung im Spectrum", Z.Psychol. Physiol. Sinnesorg., 4:241-347.

212. D.H. Krantz (1972), "Visual Scaling", (pp.660-689) in: D. Jameson and L.M. Hurvich (eds), Handbook of Sensory Physiology, Vol.VII/4, Visual Psychophysics, Berlin, Springer.

213. J. von Kries (1877), "Über die Ermüdung des Sehnerven", Arch.Ophthal., 23:17-19.

214. J. von Kries (1904), "Die Gesichtsempfindungen", (pp.109-282) in: W. Nagel (ed), Die Physiologie der Sinne III., Braunschweig, Vieweg.

215. J. von Kries (1905), "Die Gesichtsempfindungen", (pp.109-282) in: W. Nagel (ed), Handbuch der Physiologie der Menschen, Teil III., Braunschweig, Vieweg.

216. J. von Kries (1911), "Die Theorien des Licht- und Farbensinnes", (pp.366-369) in: W. Nagel (ed), Handbuch der Physiologisches Optik, II., Hamburg, Leopold Voss.

217. A.A. Kruithof (1955), "Chromatic adaptation with near white backgrounds", Die Farbe, 4: 147-158.

218. A.A. Kruithof and P.J. Bouma (1942), "Hue estimation of surface colours as influenced by the colours of the surrounding", Physica, 9:957-966.

219. E.H. Land (1959), "Color vision and the natural image (Parts I and II)", Proc.Nat.Acad.Sci. (Washington), 45:115-129 & 636-644.

220. E.H. Land (1962), "Colour in the natural image", Proc.Roy.Inst.Gt.Brit., 39:1-12.

221. E.H. Land (1964), "The retinex", Amer.Scientist, 52:247-264.

222. E.H. Land and J.J. McCann (1971), "Lightness and the retinex theory", J.Opt.Soc.Amer.,61:1-11.

223. J. Larimer, D.H. Krantz and C.M. Cicerone (1974), "Opponent-process additivity - I: Red/green equilibria", Vis.Res., 14:1127-1140.

224. J. Larimer, D.H. Krantz and C.M. Cicerone (1975), "opponent process additivity - II. Yellow/blue equilibria and nonlinear models", Vis. Res., 15:723-731.

225. M. Lie (1969), "Psychophysical invariants of

achromatic colour vision. I. The multidimensionality of achromatic colour experience", Scandinavian J.Psychol., 10:167-175.

226. R.D. Luce and J.W. Tukey (1964), "Simultaneous conjoint measurement: A new type of fundamental measurement", J.Math.Psychol., 1: 1-27.

227. D.L. MacAdam (1937), "Projective transformations of ICI color specifications", J.Opt.Soc. Amer., 27:294-303.

228. D.L. MacAdam (1943), "Specification of small chromaticity differences", J.Opt.Soc.Amer., 33:18-26.

229. D.L. MacAdam (1949), "Measurement of the influence of local adaptation on color matching", J.Opt.Soc.Amer., 39:454-459.

230. D.L. MacAdam (1955), "Influence of chromatic adaptation on color discrimination and color perception", Die Farbe, 4:133-143.

231. D.L. MacAdam (1956), "Chromatic adaptation", J.Opt.Soc.Amer., 46:500-513.

232. D.L. MacAdam (1958), "Beat frequency hypothesis of color perception", in: Visual Problems of Colour. II., London, H.M. Stationery Office.

233. D.L. MacAdam (1961), "A nonlinear hypothesis for chromatic adaptation", Vis.Res., 1: 9-41.

234. D.L. MacAdam (1963), "Chromatic adaptation. II. Nonlinear hypothesis", J.Opt.Soc.Amer., 53:1441-1445.

235. D.L. MacAdam (1970), Sources of Color Science, Cambridge (Massachusetts), The MIT Press.

236. W.R. Mackavey, S.H. Bartley and C. Casella (1962), "Disinhibition in the human visual system", J.Opt.Soc.Amer., 52:85-88.

237. R.B. MacLeod (1940), "Brightness constancy in unrecognized shadows", J.Exp.Psychol., 27:1-22.

238. R.B. MacLeod (1947), "The effects of artificial penumbrae on the brightness of included areas", (pp.138-154) in: Miscellanae Psychologica Albert Michotte, Louvain, Institut superieur de philosophie.

239. E.J. MacNichol and G. Svaetichin (1958), "Electric responses from the isolated retinas of

fishes", Amer.J.Ophthal., 46:26-40.

240. L.E. Marks (1968), "Stimulus-range, number of categories, and form of the category-scale", Amer.J.Psychol., 81:467-479.

241. L.E. Marks (1974a), Sensory Processes, The New Psychophysics, New York, Academic Press.

242. L.E. Marks (1974b), "On scales of sensation: Prolegomena to any future psychophysics that will be able to come forth as a science", Percept.Psychophys., 16:358-376.

243. W.B. Marks, W.H. Dobelle and E.F. MacNichol, Jr. (1964), "Visual pigments of single primate cones", Science, 145:1181-1183.

244. M.F. Martin (1922), "Film, surface and bulky colors and their intermediates", Amer.J. Psychol., 33:451-480.

245. L. Matin (1962), "Binocular summation at the absolute threshold of peripheral vision", J.Opt.Soc.Amer., 52:1276-1286.

246. J.J. McCann, S.P. McKee and T.H. Taylor (1976), "Quantitative studies in retines theory. A comparison between theoretical predictions and observer response to the 'color Mondrian' experiments", Vis.Res., 16:445-458.

247. C. McCollough (1965), "Color adaptation of edge-detectors in the human visual system", Science, 149:1115-1116.

248. J. Merkel (1888), "Die Abhängigkeit zwischen Reiz und Empfindung", Phil.Stud., 4:541-594.

249. G.E. Müller (1878), Zur Grundlegung der Psychophysik, Berlin, Gruben.

250. W. Münch and U. Schultz (1970), "Zur Berücksichtigung der Farbumstimmung in der Bewertung der Farbwiedergabe", Die Farbe, 19:130-134.

251. K.I. Naka and W.A.H. Rushton (1968), "S-potential and dark adaptation in fish", J.Physiol.(London), 194:259-269.

252. Y. Nayatani, T. Yamanaka and H. Sobagaki (1972), "Subjective estimation of color attributes for surface colors. Part I. Reproducibility of estimations", Acta Chromatica, 2:129-138.

253. S.M. Newhall (1953), Chapter 5 in: Optical Society of America Committee on Colorimetry, The Science of Color, New York, T.Y. Crowell.

254. S.M. Newhall, R.W. Burnham and J.R. Clark (1957), "Comparison of successive with simultaneous color matching", J.Opt.Soc.Amer., 47:43-48.

255. S.M. Newhall, D. Nickerson and D.B. Judd (1943), "Final report of the OSA subcommittee on the spacing of the Munsell colors", J.Opt. Soc.Amer., 33:385-418.

256. D. Nickerson (1963), "Color changes with change of light source. An unsolved problem in colorimetry", Acta Chromatica, 1:45-51.

257. W. Noddack and H. Jarczyk (1955), "Der Nachweis der Farbsehstoffe im lebenden menschlichen Auge", Die Farbe, 4:59-78.

258. E. Noteboom (1935), "Objektive un subjektive Änderung von farbigen Lichtern und Pigmenten durch einige farbiged Augenglässer", Z.Instrumentenkunde, 55:317-321.

259. V. O'Brien (1958), "Contour perception, illusion and reality", J.Opt.Soc.Amer., 48:112-119.

260. J.L. Ouweltjes (1966), "Chromatic adaptation and the specification of the colour rendering properties of light sources", (pp.739-744) in: Proceedings of the International Colour Meeting, Lucern 1965, Göttingen, Musterschmidt.

261. J.L. Ouweltjes (1970), "Chromatic adaptation and colour rendering of light sources", (pp.824-830) in: Color 69. 1st Congress of the International Colour Association, Stockholm 1969, Göttingen, Musterschmidt.

262. C.A. Padgham and J.E. Saunders (1975), The Perception of Light and Colour, London, G. Bell.

263. J. Paris and A.M. Prestrude (1975), "On the mechanisms of the interocular light adaptation effect", Vis.Res., 15:595-603.

264. D.S. Pearson, C.B. Rubinstein and G.J. Spivak (1969), "Comparison of perceived color in two-primary computer-generated artificial images with predictions based on the Helson-Judd formulation", J.Opt.Soc.Amer., 59: 644-658.

265. J. Pfanzagl (1959), "A general theory of measurement: Applications to utility", Naval Res. Logistics Qtrly. (Washington), 6:283-294.

266. I.T. Pitt and L.M. Winter (1974), "Effect of surround on perceived saturation", J.Opt. Soc.Amer., 64:1328-1331.

267. J.A.F. Plateau (1872), "Sur la mesure des sensations physiques, et sur la loi qui lie l'intensité de ces sensations à l'intensité de la cause excitante", Bull.Acad.Roy.Belg., 33:376-388.

268. J.A.F. Plateau (1878), "Bibliographie analytique de principaux phénomènes subjectifs de la vision, depuis les temps ancien jusqu'a la fin du XVIIIe siècle, suive d'une bibliographie simple pour la partie écoulée du siècle actuel", Mém.acad.roy.Belg., 2 ser., 42:1-266.

269. M.R. Pointer (1974), "Color discrimination as a function of observer adaptation", J.Opt. Soc.Amer., 64:750-759.

270. M.R. Pointer and J. Ensell (1975), "Chromatic adaptation for surface color stimuli" (private communication).

271. E.C. Poulton (1968), "The new psychophysics: Six models for magnitude estimation", Psychol.Bull., 69:1-19.

272. I.G. Priest and F.G. Brickwedde (1938), "The minimum perceptible colorimetric purity as a function of dominant wavelength", J.Opt. Soc.Amer., 28:133-139.

273. D.M. Purdy (1931), "Spectral hue as a function of intensity", Amr.J.Psychol., 43:541-559.

274. A. Pütter (1918), "Studien zur Theory der Reizvorgänge", Pflügers Arch.Physiol., 171:201-261.

275. K. Richter (1975), "Experimental and theoretical description of colour adaptation", Compte rendu CIE, 18th session (in press).

276. K. Richter (1976), "Das Auge als Farbreizempfänger", BAM Report ISSN 0431-5243, October 1976, Berlin, Bundesanstalt für Materialprüfung.

277. K. Richter and N. Nicolaisen (1975), "An experimental and theoretical description of colour adaptation as a function of the hue, saturation and luminance of the surrounding field", BAM Report Ri 1562, September 1975, Berlin, Bundesanstalt für Materialprüfung.

278. D.S. Riggs (1963), The Mathematical Approach to Physiological Problems, Cambridge (Massachusetts), The MIT Press.

279. S.C.H. Rowe (1972), Subjective Scaling of Hue and Saturation, London, The City University.

280. W.A.H. Rushton (1958), "Kinetics of cone pigments measured objectively on the living human fovea", Annals N.Y.Acad.Sci., 74:291-304.

281. W.A.H. Rushton (1963a), "A cone pigment in the protanope", J.Physiol.(London), 168:345-359.

282. W.A.H. Rushton (1963b), "The density of chlorolabe in the foveal cones of the protanope", J.Physiol.(London), 168:360-373.

283. W.A.H. Rushton (1963c), "Cone pigment kinetics in the protanope", J.Physiol.(London), 168:374-388.

284. W.A.H. Rushton (1965a), "A foveal pigment in the deuteranope", J.Physiol.(London), 176: 24-37.

285. W.A.H. Rushton (1965b), "Cone pigment kinetics in the deuteranope", J.Physiol.(London), 176:38-45.

286. W.A.H. Rushton (1965c), "Bleached rhodopsin and visual adaptation", J.Physiol. 181:645-655.

287. W.A.H. Rushton (1965d), "The Ferrier lecture: Visual adaptation", Proc.Roy.Soc.(London), 162:20-46.

288. W.A.H. Rushton and H.D. Baker (1963), "Effect of a very bright flash on cone vision and cone pigments in man", Nature, 200:421-423.

289. W.A.H. Rushton and G.H. Henry (1968), "Bleaching and regeneration of cone pigments in man", Vis.Res., 8:617-631.

290. C.L. Sanders (1955), "Comparison of binocular color matches with the matches expected from the trichromatic theory of vision", Die Farbe, 4:172-177.

291. C.L. Sanders and G. Wyszecki (1957), "Correlate for lightness in terms of CIE-tristimulus values. Part I.", J.Opt.Soc.Amer., 47:398-404.

292. C.L. Sanders and G. Wyszecki (1958), "L/Y ratios in terms of CIE-chromaticity coordinates", J.Opt.Soc.Amer., 48:389-392.

293. C.L. Sanders and G. Wyszecki (1964), "Correlate for brightness in terms of C.I.E. colour-matching data", Compte rendu CIE 15e session, 221-230.

294. A. Sandusky (1974), "Memory processes and judgment", (pp.61-84) in: E.C. Carterette and M.P. Friedman (eds), Handbook of Perception.

Vol.II, Psychophysical Judgment and Measurement, New York, Academic Press.

295. H. Scheibner (1963), "Untersuchungen zur Farbumstimmung des menschlichen Auges", Die Farbe, 12:6-58.

296. H. Scheibner (1966), "Adaptive color shifts", J.Opt.Soc.Amer., 56:938-942.

297. C. Scherffer (1765), Abhandlung von den zufälligen Farben, Heidelberg (privately printed).

298. C. Scherffer (1785), "Observations sur la physique", Mem.acad.roy.Franc., 26:175-187 & 273-290.

299. H.K. Schjelderup (1918), "Über die Abhängigkeit zwischen Empfindung und Reiz", Z.Psychol., 80:226-243.

300. B. Schneider and H. Lane (1963), "Ratio scales, category scales, and variability in the production of loudness and softness", J. Acoust.Soc.Amer., 35:1953-1961.

301. W. Schön (1874), "Einfluss der Ermüdung auf die Farbenempfindung", v.Graefes Arch.Ophthal., 20(2):273-286.

302. J.F. Schouten and L.S. Ornstein (1939), "Measurements on direct and indirect adaptation by means of a binocular method", J.Opt.Soc.Amer., 29:168-182.

303. T. Sellin and M.E. Wolfgang (1964), The Measurement of Delinquency, New York, Wiley.

304. L.L. Sloan (1928), "The effect of intensity of light, state of adaptation of the eye, and size of photometric field on the visibility curve", Psychological Monographs, 38:1-87 (entire No.187).

305. H. Sobagaki, T. Yamanaka, K. Takahama and Y. Nayatani (1974), "Chromatic-adaptation study by subjective-estimation method", J.Opt.Soc. Amer., 64:743-749.

306. H. Sobagaki, K. Takahama, T. Yamanaka, A. Nishimoto and Y. Nayatani (1975), "A study on chromatic adaptation by the subjective-estimation method", Compte rendu CIE 18e session (in press).

307. H. Sobagaki, K. Takahama and Y. Nayatani (1975a), "Effect of using different methods of saturation estimation on prediction of chromatic adaptation" (private communication).

308. H. Sobagaki, K. Takahama and Y. Nayatani (1975b), "Effect of illuminance of observation on saturation estimates" (private communication).

309. R.G. Speelman and J. Krauskopf (1963), "Effects of chromatic adaptation on normal and dichromatic red-green brightness matches", J.Opt.Soc.Amer., 53:1103-1107.

310. D. Steffen (1955), "Untersuchungen zur Theorie des Farbensehens", Z.Biol., 108:161-177.

311. J.C. Stevens (1957), A Comparison of Ratio Scales for the Loudness of White Noise and Brightness of White Light (Dissertation), Cambridge (Massachusetts), Harvard University.

312. J.C. Stevens and M. Guirao (1964), "Individual loudness functions", J.Acoust.Soc.Amer., 36:2210-2213.

313. S.S. Stevens (1934), "The attributes of tone", Proc.Nat.Acad.Sci.(Washington), 20:457-459.

314. S.S. Stevens (1946), "On the theory of scales of measurement", Science, 103:677-680.

315. S.S. Stevens (1951), "Mathematics, measurement and psychophysics", (pp.1-49) in: S.S. Stevens (ed), Handbook of Experimental Psychology, New York, Wiley.

316. S.S. Stevens (1971), "Sensory power functions and neural events", (pp.226-242) in: W.R. Loewenstein (ed), Handbook of Sensory Physiology, Vol.I, Principles of Receptor Physiology, Berlin, Springer.

317. S.S. Stevens (1975), Psychophysics. Introduction to its Perceptual, Neural and Social Prospects, New York, Wiley.

318. S.S. Stevens and H.B. Greenbaum (1966), "Regression effect in psychophysical judgment", Percept.Psychophys., 1:439-446.

319. S.S. Stevens and E.C. Poulton (1956), "The estimation of loudness by unpracticed observers", J.Exp.Psychol., 51:71-78.

320. W.S. Stiles (1949), "Increment thresholds and the mechanisms of colour vision", Doc.Ophthal., 3:138-163.

321. W.S. Stiles (1959), "Colour vision: The approach through increment-threshold sensitivity", Proc.Nat.Acad.Sci.(Washington), 45:100-114.

322. W.S. Stiles (1961), "Adaptation, chromatic adaptation, colour transformation", Anales d.t.

Real Soc.Esp.d.Fis.y Quim., 57:149-156.

323. Y. Sugiyama and T. Fukuda (1960), "Comparison of different UCS by using MacAdam ellipses and Munsell scales", J.Appl.Phys.(Japan), 29:480-487.

324. K. Takahama, H. Sobagaki and Y. Nayatani (1975), "Analysis of chromatic-adaptation effect by an interlinkage model" (private communication).

325. R. Teghtsoonian (1971), "On the exponents in Stevens' law and the constants in Ekman's law", Psychol.Rev., 78:71-80.

326. R. Teghtsoonian (1973), "Range effects in psychophysical scaling and a revision of Stevens' law", Amer.J.Psychol., 86:3-27.

327. H. Terstiege (1967), "Untersuchungen zum Persistenz- und Koeffizientensatz", Die Farbe, 16:1-120.

328. H. Terstiege (1972), "Chromatic adaptation. A state-of-the-art report", J.Color & Appear., 1:19-24.

329. J.P. Thomas (1963), "Relation of brightness contrast to inducing stimulus output", J.Opt. Soc.Amer., 53:1033-1037.

330. F.H. Thomas, F.L. Dimmick and S.M. Luria (1961), "A study of binocular color mixture", Vis. Res., 1:108-116.

331. L.L. Thurstone (1927a), "A law of comparative judgment", Psychol.Rev., 34:273-286.

332. L.L. Thurstone (1927b), "Psychophysical Analysis", Amer.J.Psychol., 38:368-389.

333. E.B. Titchner (1905), Experimental Psychology: A Manual of Laboratory Practice, Vol.II., New York, MacMillan.

334. E.B. Titchner (1910), A Text-Book of Psychology, New York, MacMillan.

335. G. Tonnquist (1975), Comparison Between CIE and NCS Colour Spaces, FOA Report No.C 30032-E1, Stockholm, Försvarets Forskningsanstalt.

336. W.S. Torgerson (1954), "A law of categorical judgment", Amer.Psychologist, 7:408-416.

337. W.S. Torgerson (1958), Theory and Methods of Scaling, New York, Wiley.

338. L.T. Troland (1929/1930), Principles of Psychophysiology. Vols. I & II., New York, Van Nostrand.

339. A. Tschermak von Seysenegg (1941), "Die Bedeutung der Neutralstimmung des Auges für Farbmessung und -musterung", Licht, 11:66-71.

340. A. Tschermak von Seysenegg (1952), Introduction to Physiological Optics, Springfield, C. Thomas.

341. A. Valberg (1974), "Color induction: Dependence on luminance, purity, and dominant or complementary wavelength of inducing stimuli", J.Opt.Soc.Amer., 64:1531-1540.

342. A. Valberg (1975), "Light adaptation and the saturation of colours", Vis.Res., 15: 401-404.

343. H. Voeste (1898), "Messende Versuche über die Qualitätsänderungen der Spectralfarben in Folge von Ermüdung der Netzhaut", Z.Psychol. Physiol. Sinnesorg., 18:257-267.

344. H.G. Wagner (1969), "Zur Bestimmung der grünen Grundvalenz" in: Color 69. Proceedings of the 1st AIC Congress, Stockholm 1969, Göttingen, Musterschmidt.

345. G. Wald (1937), "Photo-labile pigments in the chicken retina", Nature, 140:545-546.

346. G. Wald, P.K. Brown and P.H. Smith (1955), "Iodopsin", J.Gen.Physiol., 38:623-681.

347. H. Wallach (1948), "Brightness constancy and the nature of achromatic colors", J.Exp.Psychol., 36:119-126.

348. G.L. Walls (1960), "Land! Land!", Psychol.Bull., 57:29-48.

349. J. Walraven (1976), "Discounting the background - the missing link in the explanation of chromatic induction", Vis.Res., 16:289-295.

350. P.L. Walraven, A.M.J. Van Hout and H.J. Leebeek (1966), "Fundamental response curves of a normal and deuteranomalous observer derived from chromatic adaptation data", J.Opt.Soc. Amer., 56:125-127.

351. H.V. Walters (1942), "Some experiments on the trichromatic theory of vision", Proc.Roy. Soc.(London), 131:27-50.

352. E.G.T. Wassef (1958), "Investigations into the theory of prediction of the appearance of colours and its bearing on the theory of colour vision", Optica Acta, 5:101-108.

353. E.G.T. Wassef (1959), "Linearity of the relationship between the tristimulus values of corresponding colours seen under different conditions of chromatic adaptation", Optica Acta, 6:378-383.

354. E.G.T. Wassef and E. Aziz (1960), "Changes in the position of the invariant colours with the state of adaptation of the eye", Optica Acta, 7:341-354.

355. E.H. Weber (1834), De pulsu, resorptione, auditu et tactu; annotationes anatomicae et physiologicae, Leipzig, Köhler.

356. T.N. Wiesel and D.H. Hubel (1966), "Spatial and chromatic interactions in the lateral geniculate body of the Rhesus monkey", J.Neurophysiol., 29:1115-1156.

357. R.S. Woodworth (1938), Experimental Psychology, New York, Holt, Rinehart and Winston.

358. M.M. Woolfson (1959), "Some new aspects of color perception", IBM J.Res., 3:313-315.

359. B. Wooten (1970), The Effects of Simultaneous and Successive Chromatic Contrast on Spectral Hue (Dissertation), Providence (Rhode Island), Brown University.

360. W.D. Wright (1934), "The measurement and analysis of colour adaptation phenomena", Proc. Roy.Soc.(London), 115B:49-87.

361. W.D. Wright (1936), "The breakdown of a colour match with high intensity of adaptation", J.Physiol.(London), 87:23-33.

362. W.D. Wright (1937), "The foveal light adaptation process", Proc.Roy.Soc.(London), 122B:220-230.

363. W.D. Wright (1944), The Measurement of Colour, 2nd Edition, London, Hilger.

364. W.D. Wright (1946), Researches on Normal and Defective Colour Vision, London, H. Kimpton.

365. W.D. Wright and F.G.H. Pitt (1935), "The colour-vision characteristics of two trichromats", Proc.Phys.Soc.(London), 47:207-208.

366. W. Wundt (1874), Grundzüge der physiologischen Psychologie, Laipzig, Engelmann.

367. W. Wundt (1907), Outlines of Psychology (translated by C.H. Judd), Leipzig, Engelmann.

368. G. Wyszecki (1954a), "A graphical interpretation of a three-components theory of chromatic adaptation in terms of the CIE-chromaticity diagram", J.Opt.Soc.Amer., 44:787-792.

369. G. Wyszecki (1954b), "A regular rhombohedral lattice sampling of Munsell Renotation space", J.Opt.Soc.Amer., 44:725-730.

370. G. Wyszecki (1974), "CIE colorimetry committee working program on color differences", J.Opt.Soc.Amer., 64:896.

371. G. Wyszecki and C.L. Sanders (1957a), "Correlate for lightness in terms of CIE-tristimulus values. Part II.", J.Opt.Soc.Amer., 47: 840-842.

372. G. Wyszecki and C.L. Sanders (1957b), "Additional studies of the correlate of lightness in terms of CIE-tristimulus values", J.Opt. Soc.Amer., 47:1338.

373. G. Wyszecki and W.S. Stiles (1967), Color Science: Concepts and Methods, Quantitative Data and Formulas, New York, Wiley.

374. E. Zinner (1930), "Die Reizempfindungskurve", Z.Sinnesphysiol., 61:247-266.

375. J.P. Zubek and G. Welch (1963), "Electroencephalographic changes after prolonged sensory and perceptual deprivation", Science, 139: 1209-1210.